# Composite asymmetric dark matter and galactic rotation curves

Ayuki Kamada (IBS-CTPU)




**Based on**
**AK, Manoj Kaplinghat, Andrew B. Pace, and Hai-bo Yu, PRL, 2017**
**Masahiro Ibe, AK, Shin Kobayashi, and Wakutaka Nakano, JHEP, 2018**
**Masahiro Ibe, AK, Shin Kobayashi, Takumi Kuwahara, and Wakutaka Nakano, JHEP, 2019**

June 11, 2019 @ Nagoya University

# Dark matter

Accumulated evidences from observations of the Universe

Known properties

- long-lived over the age of the Universe

- accounting for about 30% of the present energy density of the Universe $\Omega_{\rm dm}h^2 \simeq 5\Omega_{\rm baryon}h^2 \simeq 0.12$

- feebly-interacting with photon and baryon

- not too hot to smear out primordial density contrast

No SM particle satisfies the properties

→ long-standing mystery in cosmology and particle physics

# WIMP Miracle

Weakly interacting massive particle: WIMP

Stability: new $\mathbb{Z}_2$ symmetry  e.g., matter parity: $U(1)_{B-L} \to (-1)^{3(B-L)}$

Abundance: annihilation  $\chi\chi \to AA$  $\chi$ : WIMP  $A$ : SM

- thermal freeze-out: electoweak-scale interaction

- indirect detection (cosmic ray) experiments

Interaction with SM particles: (sub-) weak scale

- direct detection (nuclei recoil) experiments

Non-relativistic: cold dark matter

Related with electoweak-scale new physics that explains the origin of the weak scale against Planck scale (hierarchy problem)

- collider experiments

# Supersymmetry

Theory is invariant under boson ↔ fermion

Theoretical properties

- non-trivially extend space-time (Poincaré) symmetry
- control quantum corrections through chiral symmetry

Phenomenological (MSSM) properties

- SUSY breaking → Higgs potential
  - electroweak-scale SUSY → hierarchy problem
- provide a dark matter candidate $R\text{-parity} = (-1)^{3(B-L)+2s}$
- precise grand unification of gauge couplings

# No naturalness so far…

LHC discovery of 125 GeV Higgs and null-detection of top partners

- something wrong in the hierarchy problem and postulated solutions (including but not only electroweak-scale SUSY)

WIMP is no more as a miracle as we expected…

- new theoretical reasoning for WIMP?
  - mini-split SUSY
    - sfermions > 100 TeV; gauginos ~ TeV
      - 125 GeV Higgs
      - dark matter
      - precise grand unification

- observational hints: small-scale issues in structure formation?

# What I will discuss

What about others? What if WIMPs are subdominant?

Puzzles for WIMPs in structure formation — part 1

- diversity of rotation curves
- self-interacting dark matter $\sigma/m = \mathcal{O}(1)\,\mathrm{cm}^2/\mathrm{g} = \mathcal{O}(1)\,\mathrm{barn}/\mathrm{GeV}$

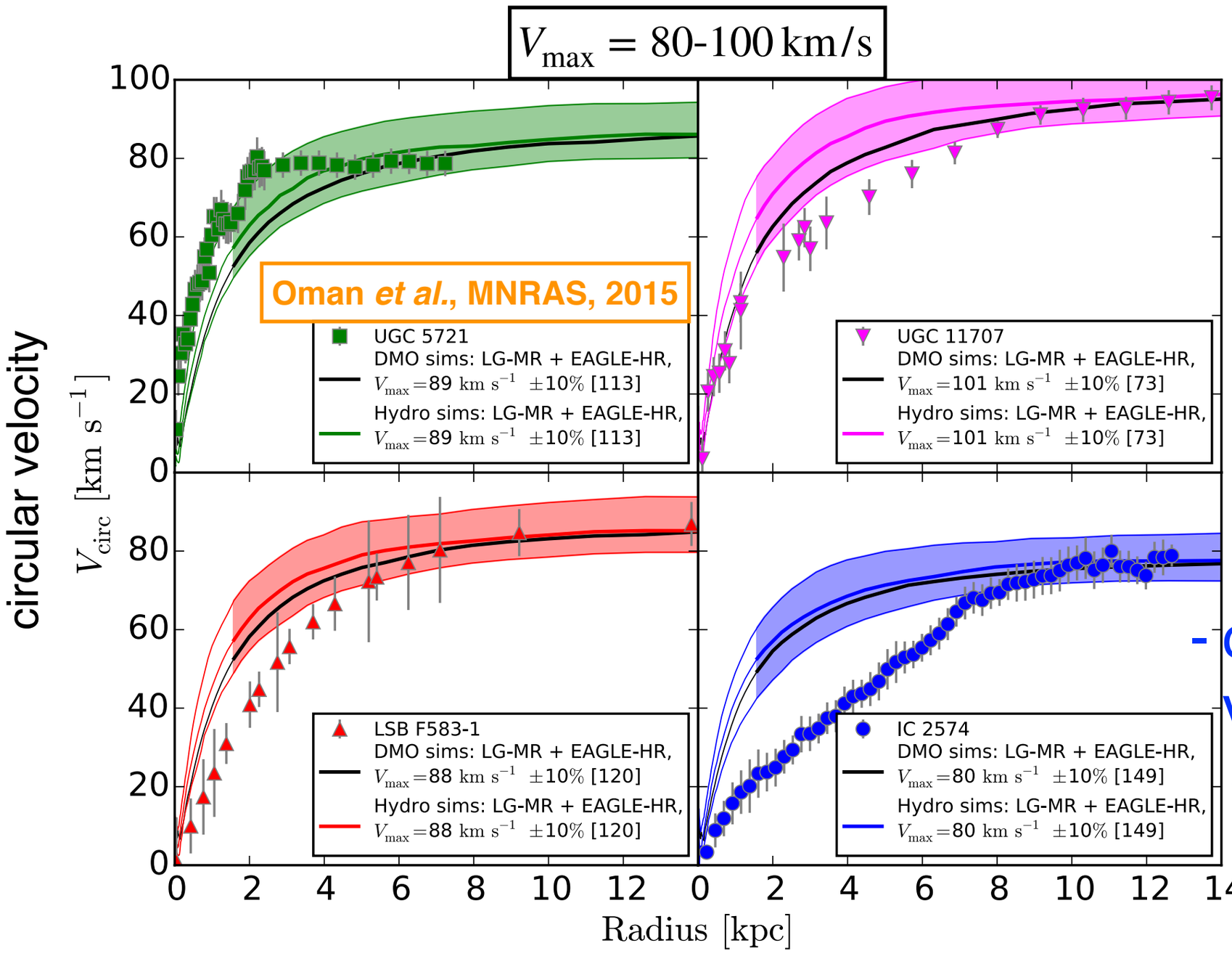
Composite asymmetric dark matter — part 2

- naturally realize self-interacting dark matter
- simple model → ultraviolet completion

# Part 1: Diversity of inner rotation curves

Collisionless dark matter prediction: inner circular velocity is almost uniquely determined by outer circular velocity

↔ observations show diversity




✳ unique prediction is related with the concentration-mass relation

- overpredict the circular velocity by a factor of $\sim 2$ ( $\sim 4$ in mass)

# Possible solutions

The issues may be attributed to incomplete understanding of complex astrophysical processes (subgrid physics)

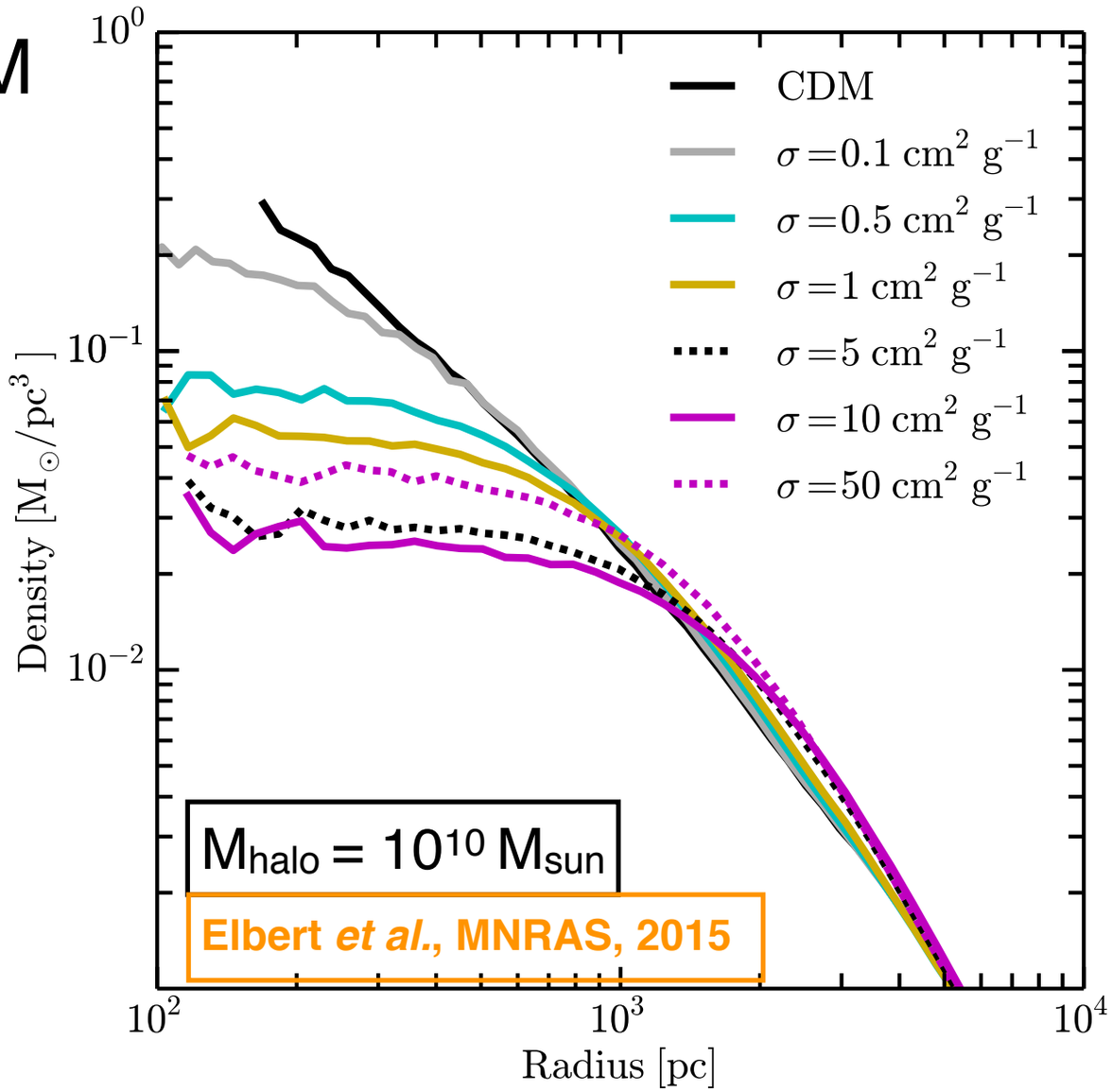
The issues may indicate alternatives to CDM (WIMPs)

- self-interacting dark matter: SIDM

$$\sigma/m = \mathcal{O}(1)\,\mathrm{cm}^2/\mathrm{g}$$

- reduce the central mass density

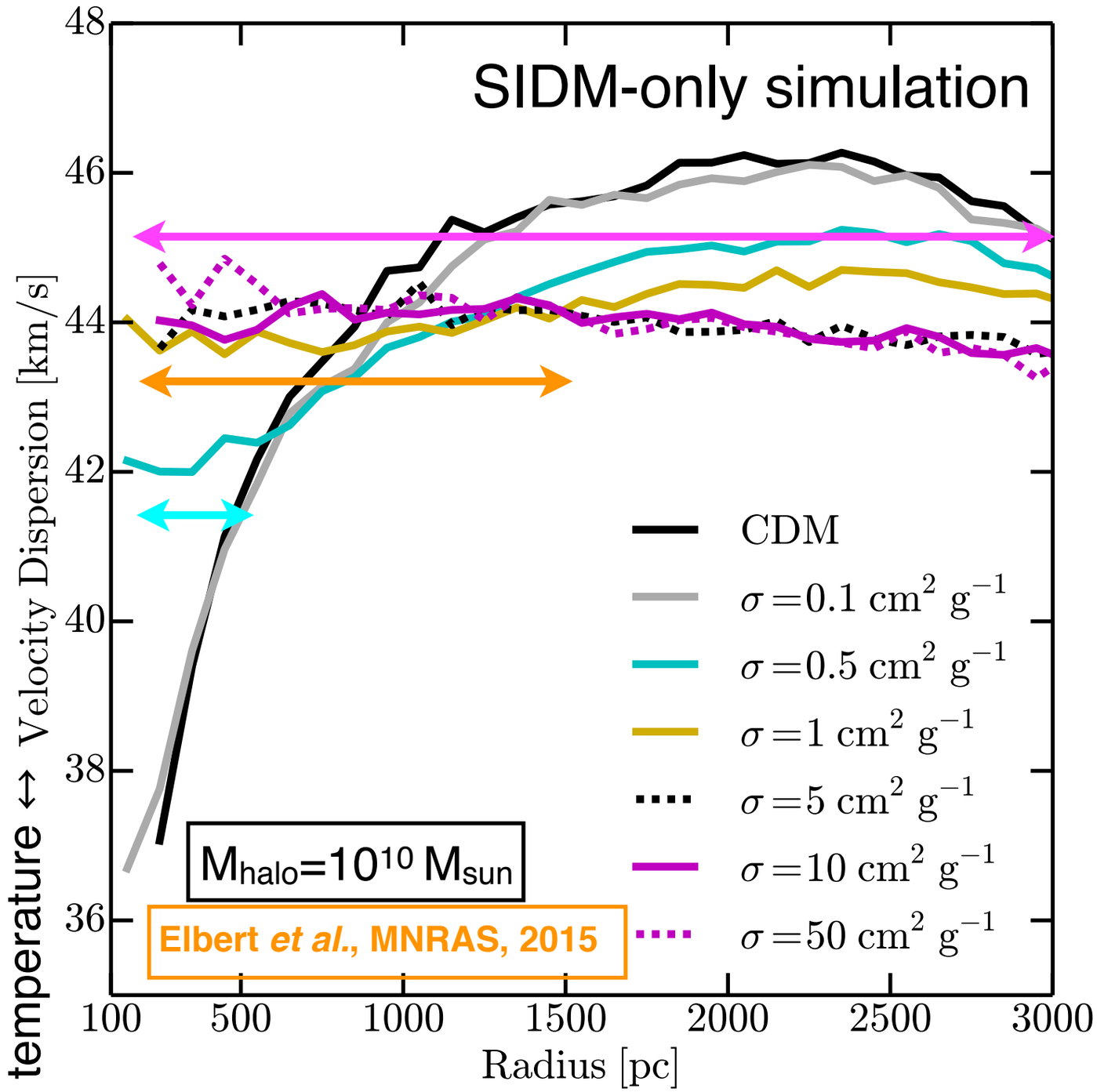
- ameliorate overprediction in some galaxies, but naively underpredict the circular velocity in other galaxies



# Iso-thermal halo

Self-scattering leads to thermalization of DM halos at $r < r_1$
where self-scattering happens at least one time until now

$$\sigma/m\,\rho(r_1)v(r_1)\,t_{\rm age} = 1$$



# Key observation

Iso-thermal → Boltzmann distribution

$$\rho_{\rm DM}(\vec{x}) = \rho^0_{\rm DM}\exp(-\phi(\vec{x})/\sigma^2)$$

$$\Delta\phi = 4\pi G(\rho_{\rm DM} + \rho_{\rm baryon})$$

- inner profile is exponentially sensitive to baryon distribution

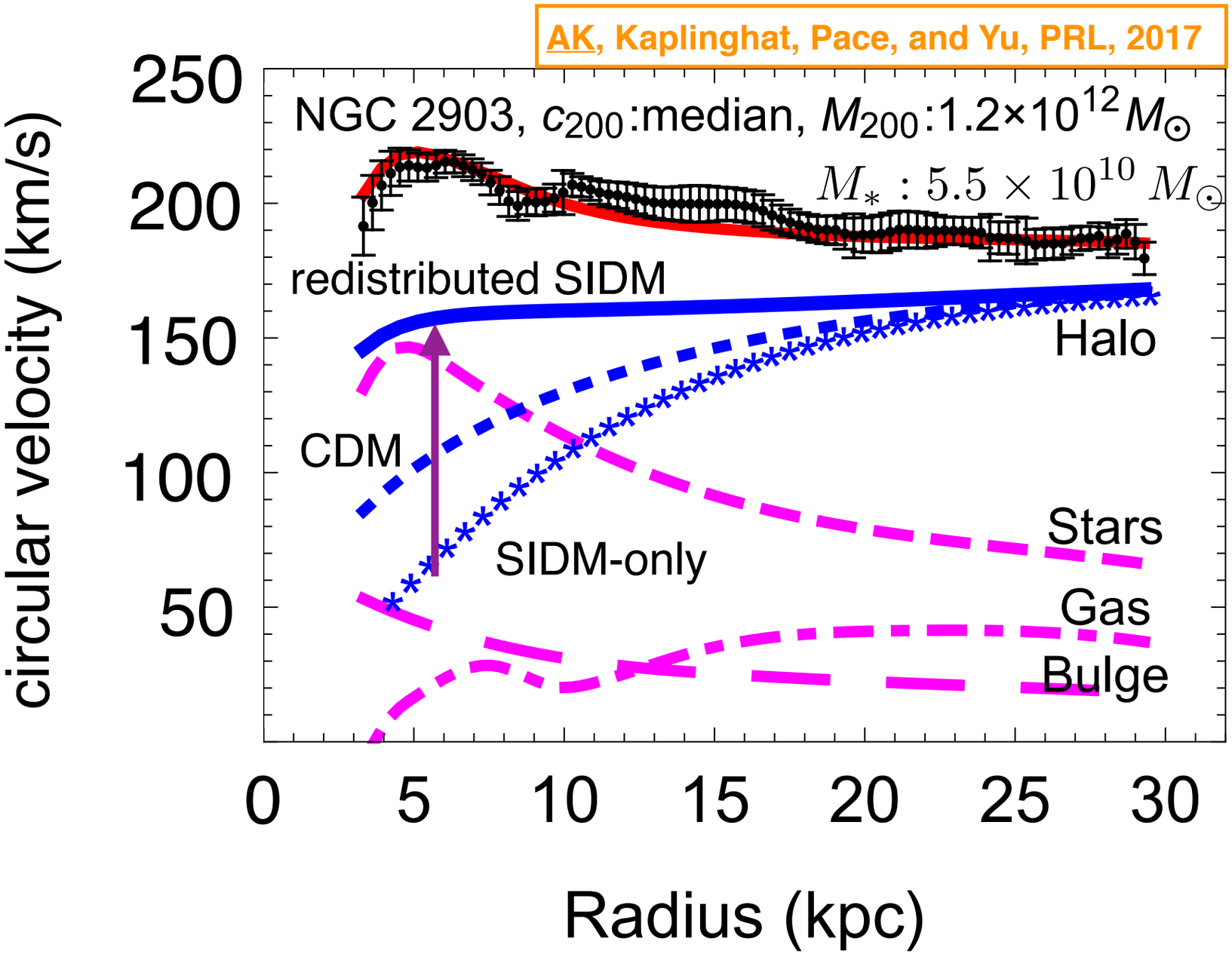
Baryons form complex objects, which show a large diversity

→ SIDM particles, redistributed according to formed baryonic objects, can show a diversity

✳ do not rely on unconstrained subgrid astrophysical processes take into account observed baryon distribution

# Impacts in observed galaxies

✳ Hereafter $\sigma/m = 3\,\mathrm{cm}^2/\mathrm{g}$




- Observed stellar disk makes SIDM inner circular velocity $\sim 3$ times higher

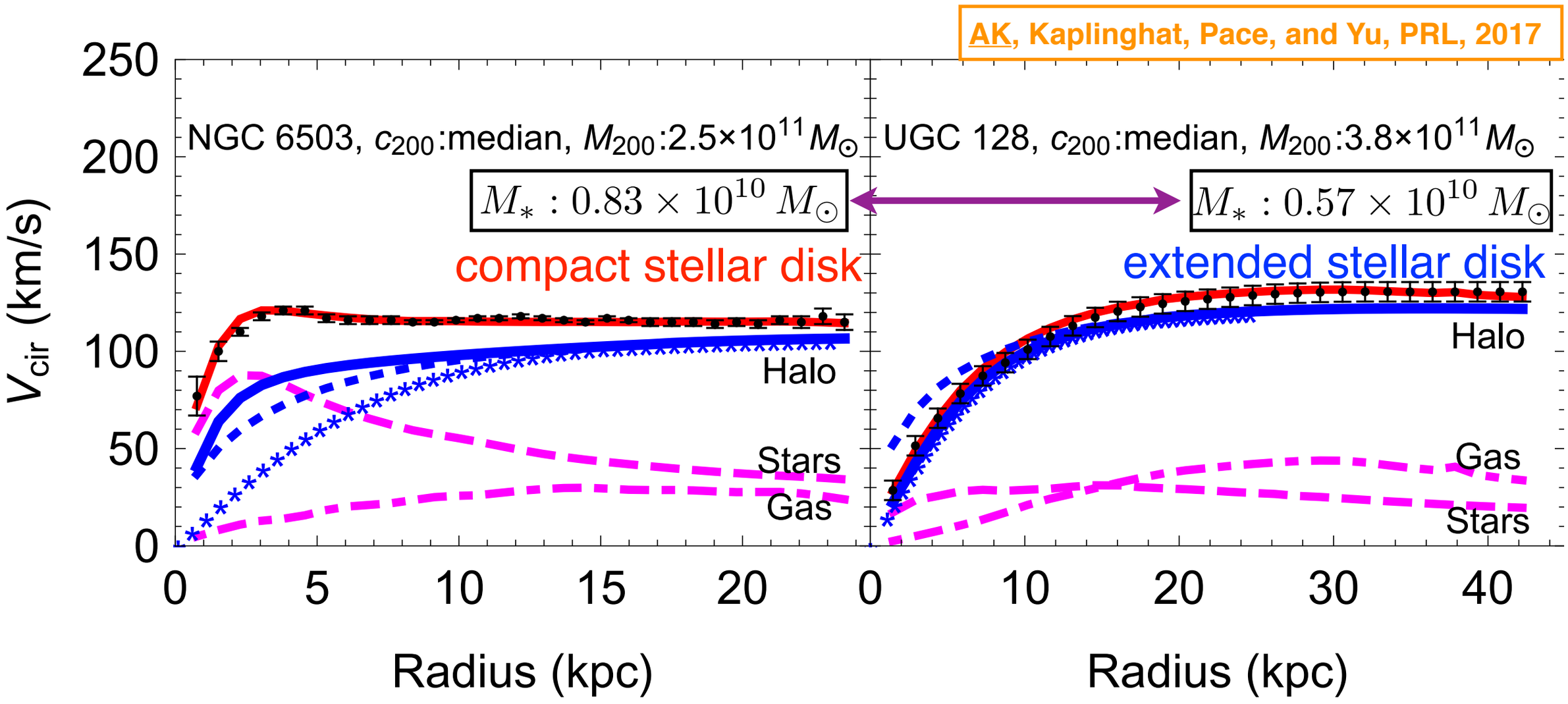
→ reproducing flat circular velocity at 10-20 kpc

# Diversity in stellar distribution

Similar outer circular velocity and stellar mass,
but different stellar distribution

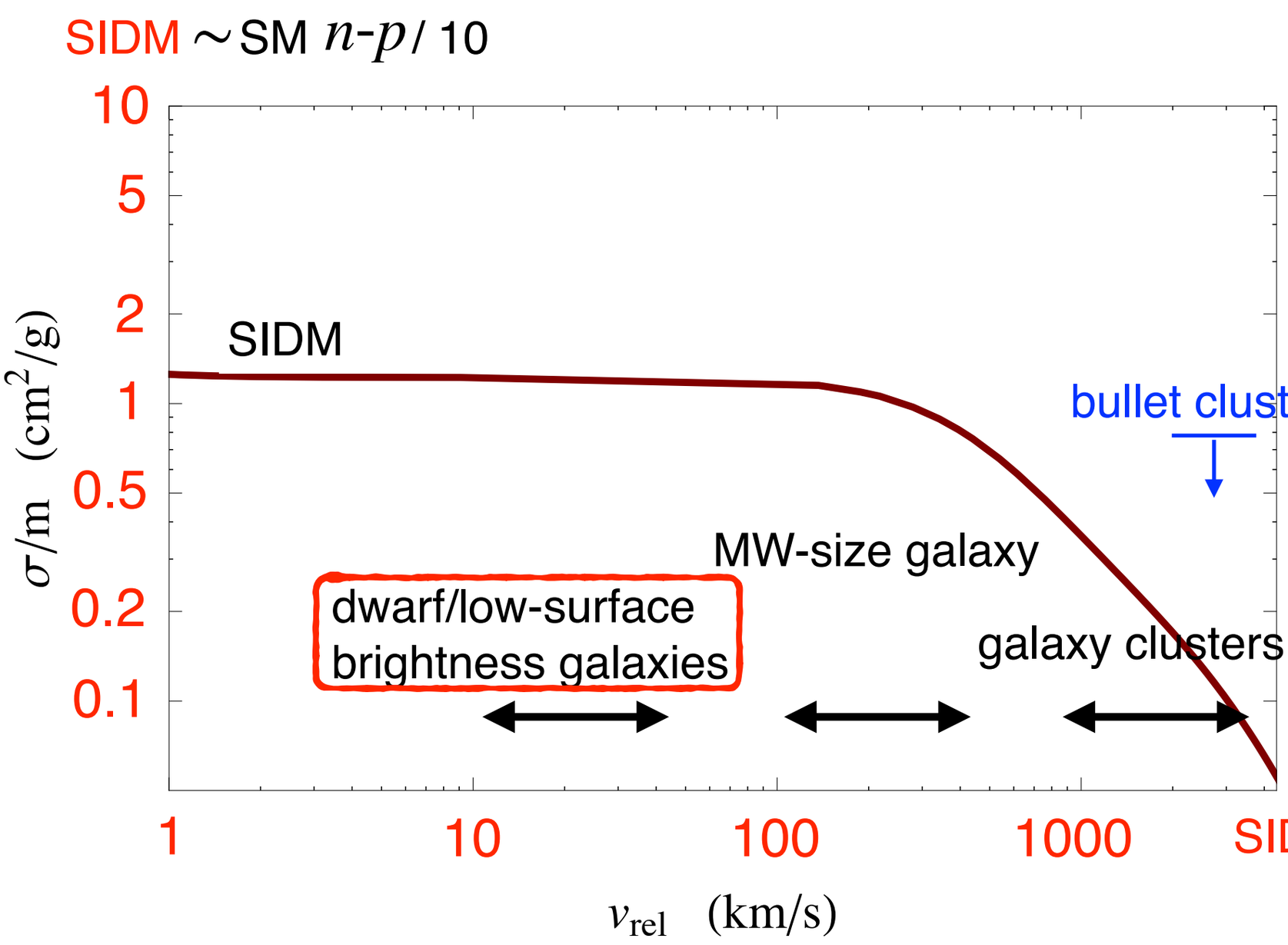
- compact → redistribute SIDM significantly

- extended → unchange SIDM distribution



# Self-interacting dark matter

SIDM cross section indicated by small-scale puzzles




- cores in dwarf galaxies

→ $\sigma/m \gtrsim 1\mathrm{cm}^2/\mathrm{g}$

- cores in galaxy clusters

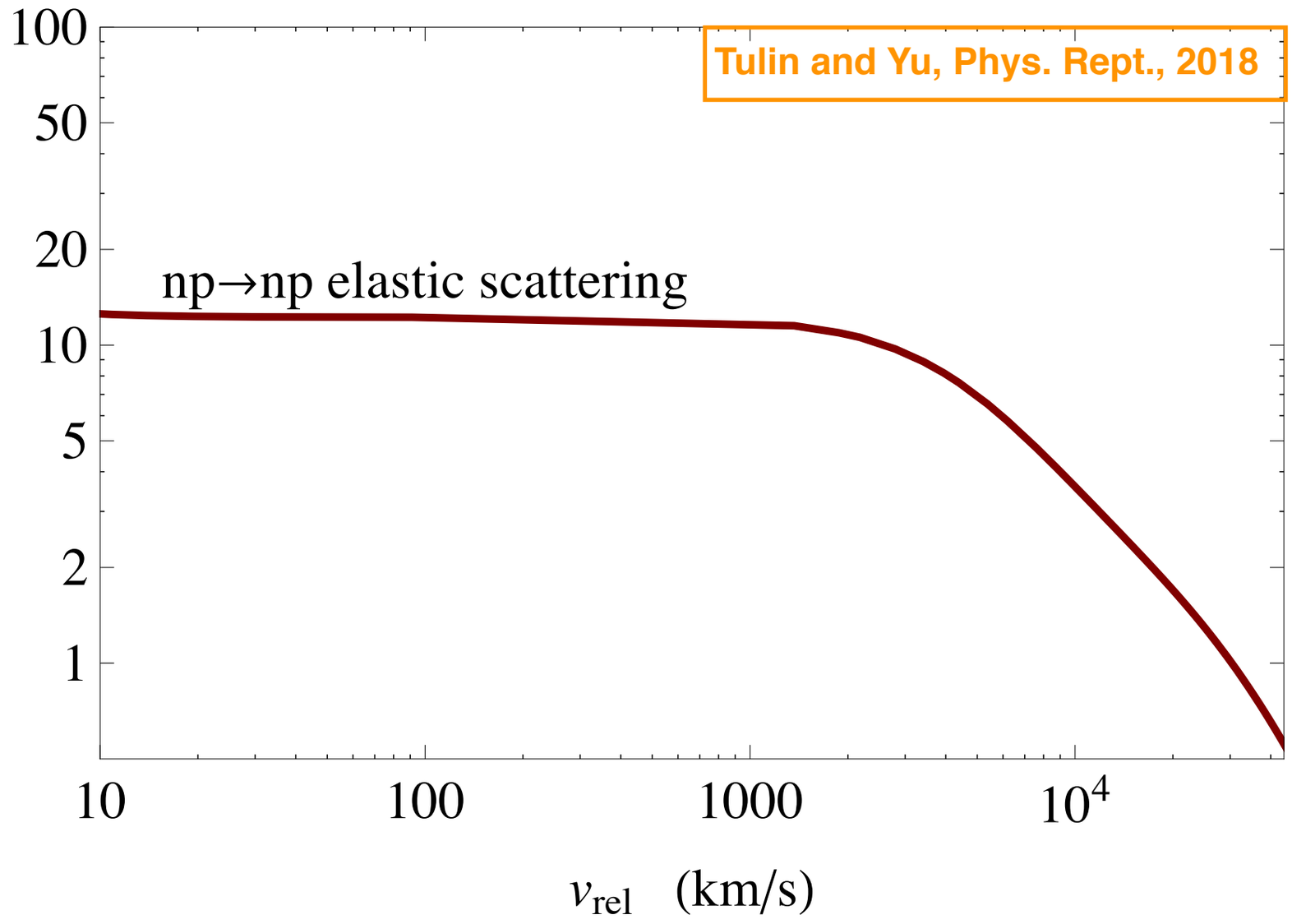
→ $\sigma/m \sim 0.1\mathrm{cm}^2/\mathrm{g}$

Kaplinghat, Tulin, and Yu, PRL, 2016

# Self-interacting dark matter

SM strong dynamics: nucleon elastic-scattering cross section

- diminishing w/ increasing velocity



# Part 2: Composite asymmetric dark matter

Why is a dark matter particle long-lived?

- new accidental $U(1)_{B'}$ (like $U(1)_B$ for proton)

- decay operator: non-renormalizable $\Lambda_{\mathrm{QCD}'}/M_* \ll 1$

- $B'$ number asymmetry - cogenesis

Portal operator

$$\mathscr{L}_{\mathrm{portal}} = \frac{1}{M_*^n}\mathcal{O}_{\mathrm{SM}}\mathcal{O}_D \ : \text{n+4 dim.}$$

✳ when no particle charged under both gauge groups

$\mathcal{O}_{\mathrm{SM}\,(D)}$ : SM (D) gauge neutral, but $U(1)_{B-L}$ ($U(1)_{B'}$) charged

→ at high energy (temperature) , $Y_{\Delta(B-L)} \leftrightarrow Y_{\Delta B'}$

$Y_{\Delta B'} \sim Y_{\Delta B}$ $\quad m_{N'} \sim \Lambda_{\mathrm{QCD}'} = \mathcal{O}(1)\,\mathrm{GeV} \rightarrow \quad \Omega_{\mathrm{dm}}h^2 \simeq 5\Omega_{\mathrm{baryon}}h^2 \simeq 0.12$

- close to SM QCD dynamical scale

# Thermal history

SM

$Y_{\Delta(B-L)} \sim Y_{\Delta B'}$

dark

portal operator decoupled $T \sim M_*(M_*/M_{\rm pl})^{1/(2n-1)}$

$U(1)_{B-L}$ $Y_{\Delta(B-L)}$

$U(1)_{B'}$ $Y_{\Delta B'}$

sphaleron process decoupled

$T \sim 100\,\mathrm{GeV}$

$U(1)_B \times U(1)_L$ $Y_{\Delta B}$ $Y_{\Delta L}$

QCD phase transition

$T \sim \Lambda_{\rm QCD}$

pair annihilation of nucleons into pions

$\rightarrow\ \Omega_{\rm baryon}h^2 \propto \Lambda_{\rm QCD} Y_{\Delta B}$

QCD' phase transition

$T \sim \Lambda_{\rm QCD'}$

pair annihilation of nucleon's

$\rightarrow\ \Omega_{\rm DM'}h^2 \propto \Lambda_{\rm QCD'} Y_{\Delta B'}$

# To be answered

Origin of the portal operator? - high-energy

- if $\frac{1}{M_*^n}\mathcal{O}_{\rm SM}\mathcal{O}_D$ and $\frac{1}{M_*^n}\mathcal{O}_{\rm SM}\overline{\mathcal{O}}_D$ coexist, asymmetry is not left

Asymmetry generation?

Fukugita and Yanagida, PLB, 1986

- compatible with, e.g., thermal leptogenesis?

Where is dark sector entropy gone? - low-energy

- $\Delta N_{\rm eff}$ from the dark sector (e.g., dark pions)

# Simple model

Ibe, AK, Kobayashi, and Nakano, JHEP 2018

Model setup: QCD×QED-like hidden sector $u'\ \bar{u}'\ d'\ \bar{d}'$

- dark nucleons as DM $p' \sim u'u'd'\quad n' \sim u'd'd'$

Right-handed neutrinos $\bar{N}$ w/ soft breaking mass $M_R$
and scalar down quark $H'_C$ w/ mass $M_{H'_C}$ $U(1)_{B-L+B'} \to (-1)^{3(B-L+B')}$

- thermal leptogenesis → $B-L$ asymmetry

- see-saw mechanism → active neutrino mass

- only $\dfrac{y_N}{M_{H_C}^2 M_R}\bar{u}'\bar{d}'\bar{d}'LH$ and ✗ $\dfrac{y_N}{M_{H_C}^2 M_R}\bar{u}\bar{d}\bar{d}LH$

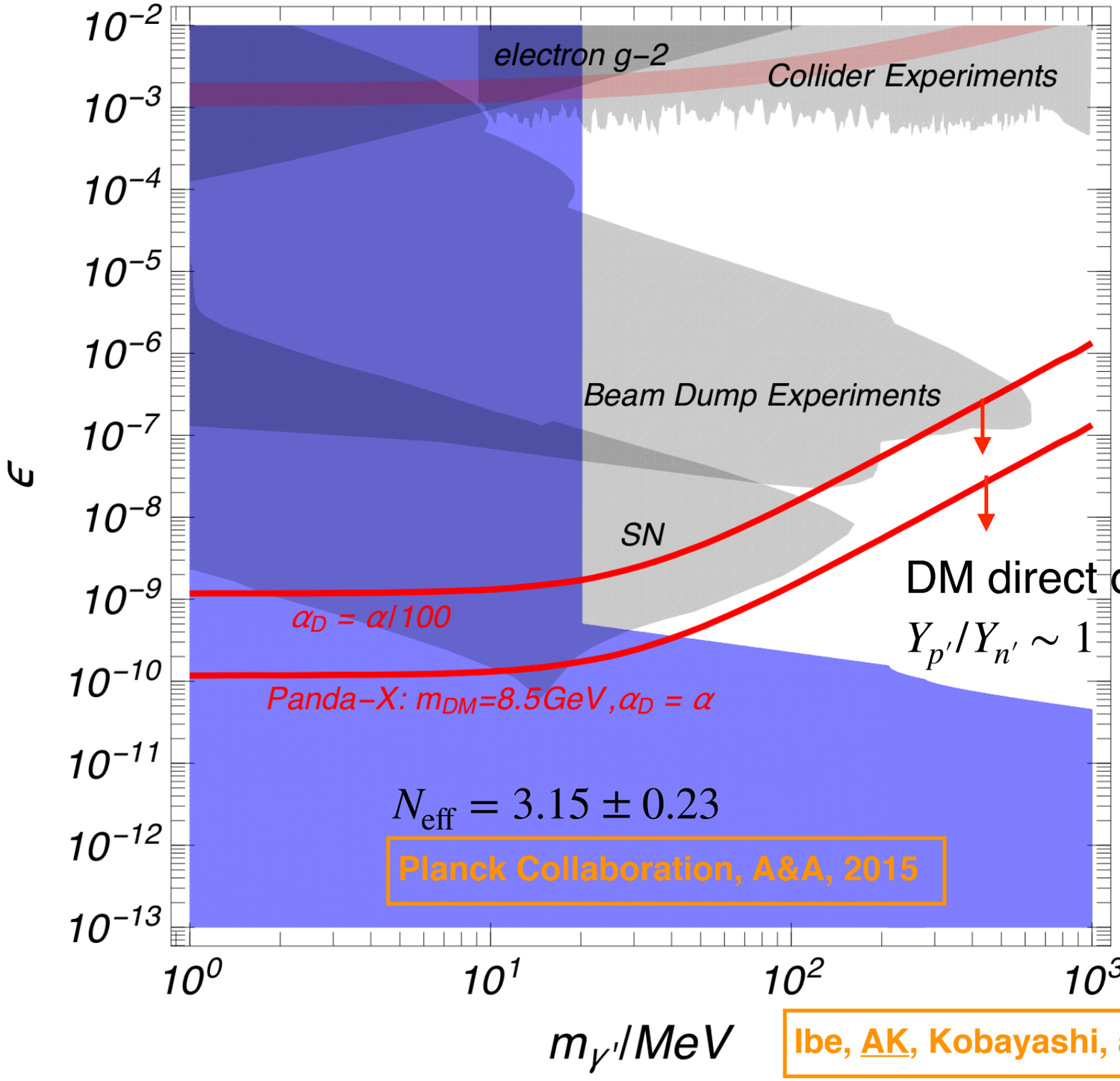
Kinetic mixing between SM and dark photons $\dfrac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$
and $U(1)'$ breaking scalar $H^{+'}$

- dark photon decay releases dark sector entropy

- direct detection: SM and dark protons scattering $Y_{p'}/Y_{n'}$?

# Dark photon parameter plot

$$\Gamma_{\gamma' \to e\bar{e}} = 0.3\,\mathrm{s}^{-1} \times \left(\frac{\epsilon}{10^{-10}}\right)^2 \left(\frac{m_{\gamma'}}{100\,\mathrm{MeV}}\right)$$




Del Nobile, Kaplinghat, and Yu, JCAP, 2015

- chance to see QCD-like asymmetric dark matter in near-future

Ibe, AK, Kobayashi, and Nakano, JHEP 2018

# Origin of kinetic mixing

Ibe, AK, Kobayashi, Kuwahara and Nakano, JHEP, 2019

Grand unifications in both SM and dark sectors $SU(5) \times SU(4)'$

✳ mass splitting

$m_{d'} < \Lambda_{\mathrm{QCD}'} < m_{e'}$

: dark nucleon decay

$M_{H'_C} \gg m_{H^{+'}}$ : portal operator

$\mathbf{6}' : (u', \bar{u}')$ $\mathbf{4}' : (d', \bar{e}')$ $\bar{\mathbf{4}}' : (\bar{d}', e')$

$\mathbf{4}'_H : (H'_C, H^{+'})$ - $U(1)'$ breaking

- portal operator

- particles we introduce so far except for $e'$ form $SU(4)'$ multiplets

Higher dimensional operator

$$\mathscr{L}_{\mathrm{mix}} \sim \frac{1}{M_{\mathrm{pl}}^2} \mathrm{Tr}\left(F_{\mathrm{GUT}\mu\nu}\Sigma_{\mathrm{GUT}}\right) \mathrm{Tr}\left(F^{\mu\nu}_{\mathrm{GUT}'}\Sigma_{\mathrm{GUT}'}\right)$$

Σ: adjoint scalar

$$\to 10^{-10} \left(\frac{v_{24}}{10^{16}\,\mathrm{GeV}}\right)\left(\frac{v_{15}}{10^{10}\,\mathrm{GeV}}\right) F_{\mu\nu}F'^{\mu\nu}$$

$$\sim M_{H_C} > M_R > 10^9\,\mathrm{GeV}$$

# Supersymmetric realization

Precise $SU(5)$ grand unification and origins of electroweak and $U(1)'$ breaking → SUSY

Ibe, AK, Kobayashi, Kuwahara and Nakano, JHEP, 2019

Dark sector $SU(4)'$ $\mathbf{6}' : (u', \overline{u}')$ $\mathbf{4}' : (d', \overline{e}')$ $\overline{\mathbf{4}}' : (\overline{d}', e')$

$$\mathbf{4}'_H : (H'_C, H^{+\prime}) \quad \overline{\mathbf{4}}'_H : (\overline{H}'_C, H^{-\prime})$$

Portal superpotential $W \sim \frac{y_N}{M_{H_C} M_R} \overline{u}' \overline{d}' \overline{d}' L H_u$

$$\overline{\widetilde{d}}' \to \mathscr{L} \sim \frac{\alpha'}{4\pi} \frac{y_N}{M_{H_C} M'_S M_R} \overline{u}' \overline{d}' \overline{d}' L H_u$$

dark nucleon decay into neutrino → $\lesssim \frac{1}{10^{26}\,\mathrm{GeV}^3}$

Covi, Grefe, Ibarra, and Tran, JCAP, 2010

Fukuda, Matsumoto, and Mukhopadhyay, PRD, 2015

$n' \to \pi^{0'} + \nu \qquad \tau \gtrsim 10^{23}\,\mathrm{sec}$

hidden sparticle mass $M'_S \gtrsim 10^3\,\mathrm{GeV} \left( \frac{M_R}{10^9\,\mathrm{GeV}} \right)^{1/2}$ - split SUSY!

# Mirror grand unification

Dream $SU(5) \times SU(4)' \to SU(5) \times SU(5)'/\mathbb{Z}_2$

Ibe, AK, Kobayashi, Kuwahara and Nakano, work in progress

$\mathbf{10} : (Q, \bar{u}, \bar{e}) \quad \bar{\mathbf{5}} : (\bar{d}, \hat{L})$

$\mathbf{5}_H : (H_C, H_u) \quad \bar{\mathbf{5}}_H : (\bar{H}_C, \hat{H}_d)$

$\mathbf{10}' : (\mathbf{6}'(u', \bar{u}') + \mathbf{4}'(d', \bar{e}'))$

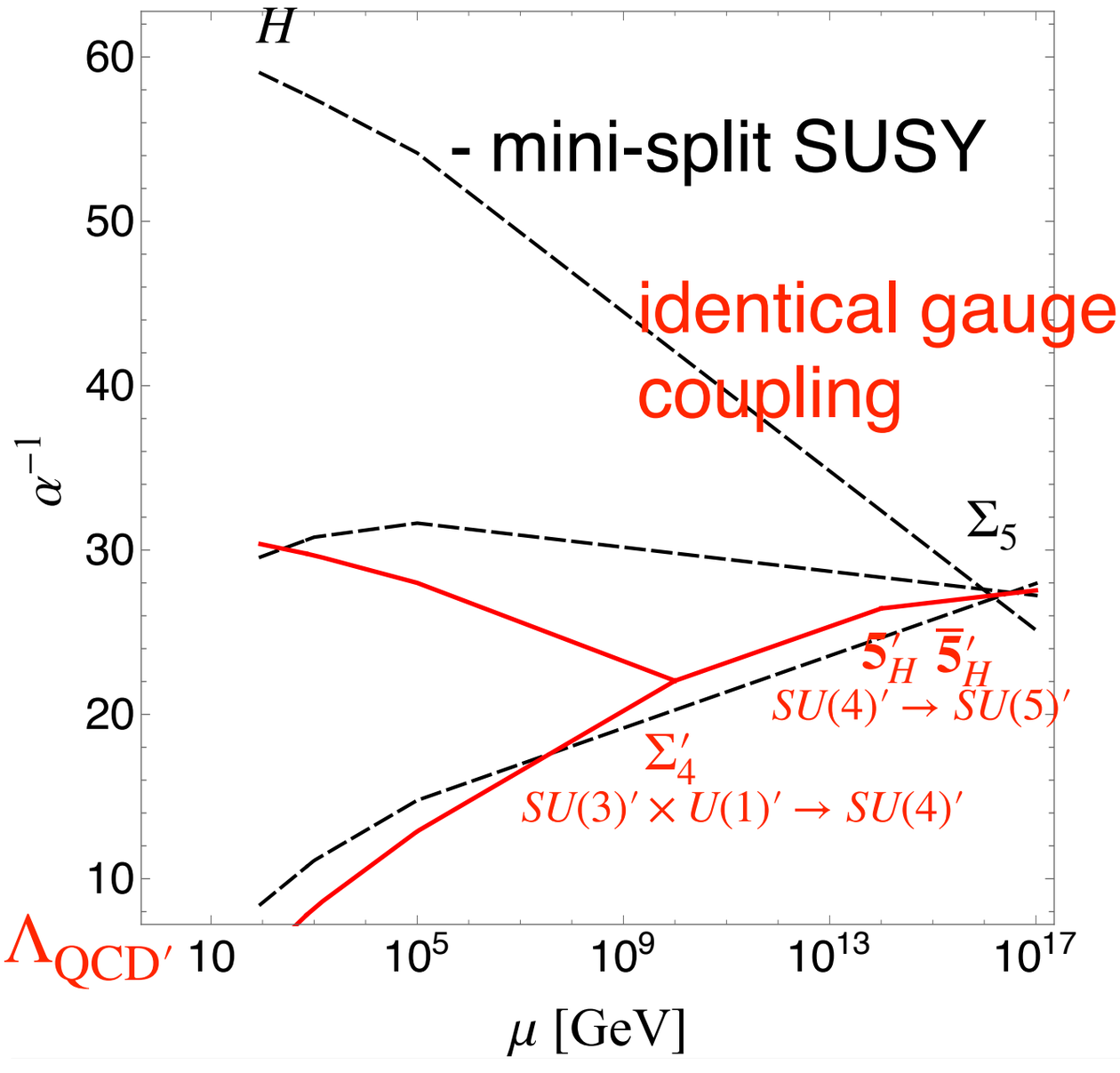
$\bar{\mathbf{5}}' : (\bar{\mathbf{4}}'(\bar{d}', e'), -\nu')$

$\mathbf{5}'_H : (\mathbf{4}'_H(H'_C, H_u^{+\prime}), H_u^{0\prime})$

$\bar{\mathbf{5}}'_H : (\bar{\mathbf{4}}'_H(\bar{H}'_C, H_d^{-\prime}), -H_d^{0\prime})$

large VEV
→ vector-like theory

- softly broken



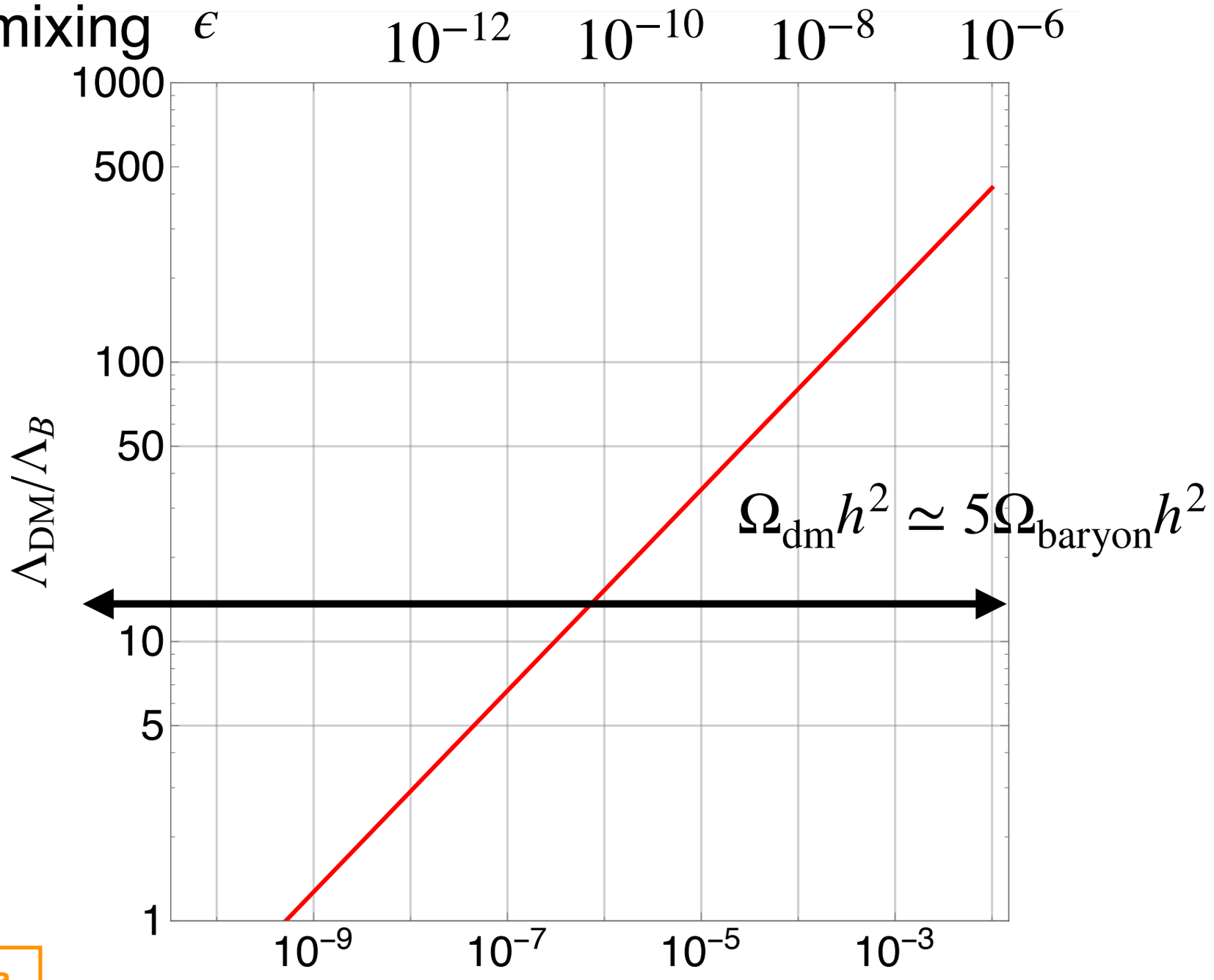

$\Lambda_{\rm QCD} \sim \Lambda_{\rm QCD'}$

# Alleviating coincidence

Why $\Omega_{\rm dm}h^2 \sim \Omega_{\rm baryon}h^2$ or $\Lambda_{\rm QCD} \sim \Lambda_{\rm QCD'}$ ?

kinetic mixing $\epsilon$

just 3 orders of magnitude




8 orders of magnitude

Ibe, AK, Kobayashi, Kuwahara and Nakano, work in progress

# Summary

WIMP miracle may have been gone…

- another WIMP miracle related with GUT?
- mini-split SUSY: origin of electroweak symmetry breaking and precise gauge couplings

Small-scale puzzles: diversity of inner rotation curves

- SIDM can explain diversity by changing its distribution according to formed baryon structure (disks)

Velocity-dependent self-scattering cross section is indicated by small-scale puzzles

Asymmetric composite DM is a plausible framework

- DM stability: dark baryon number
- DM relic abundance: co-genesis

# Summary

Simple QCD× QED-like dark sector as a working example

- right-handed neutrino: see-saw mechanisms,
  thermal leptogenesis, and generating portal operator

- dark photon decay: releasing dark sector entropy

- kinetic mixing: DM direct detection

$SU(5) \times SU(4)'$ grand unification

- mini-split SUSY: precise $SU(5)$ grand unification
  and origins of electroweak and $U(1)'$ breaking

- DM decay into neutrino and dark pion (→ SM electrons)

→ $SU(5) \times SU(5)'/\mathbb{Z}_2$ grand unification?

# Thank you for your attention

# Constraints from galaxy clusters

$V_{max}$~1000 km/s
↔ galaxy: $V_{max}$~100 km/s

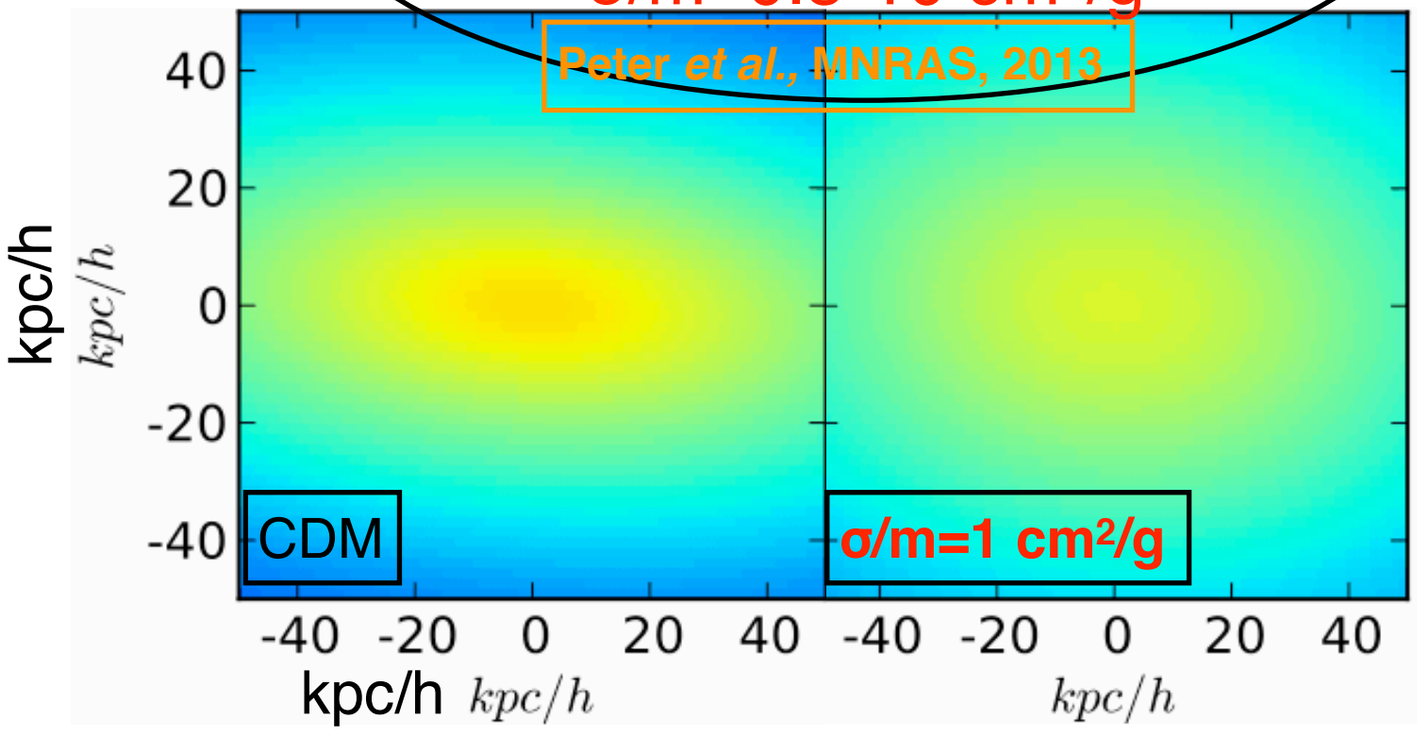
σ/m=0.5-10 cm²/g

**Halo shape - ellipticity**
**- galaxy cluster MS 2137–23**
**(e=0.18@r=70 kpc)**
**(estimate) σ/m<0.02 cm²/g**

Miralda-Escudé *et al.*, ApJ, 2002

**(simulation/l.o.s. effect)**
**σ/m<1 cm²/g**

Peter *et al.*, MNRAS, 2013

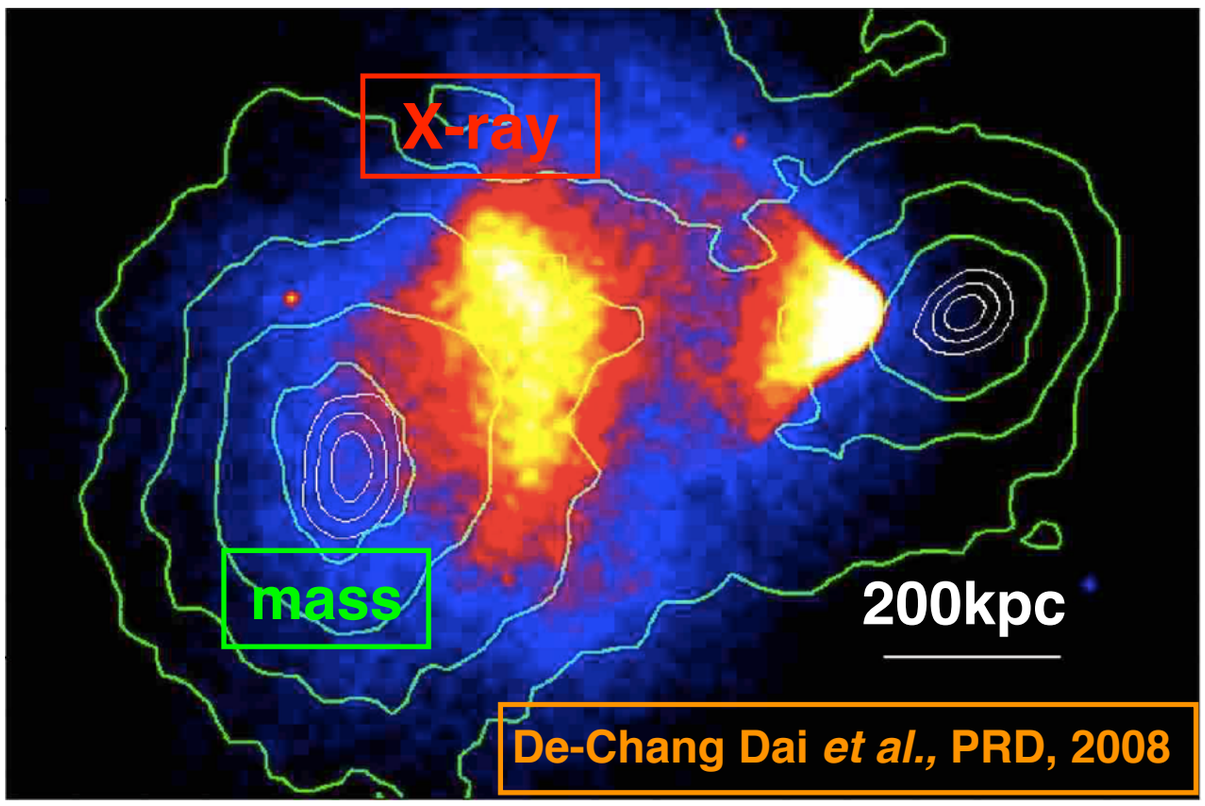



**Bullet cluster - transparency**
**- 1E0657-558**
**(offset) σ/m<1.25 cm²/g**
**(massloss) σ/m<0.7 cm²/g**

Randall *et al.*, ApJ, 2008

**- an ensemble (72)**
**(offset) σ/m<0.47 cm²/g**

Harvey *et al.*, Science, 2015

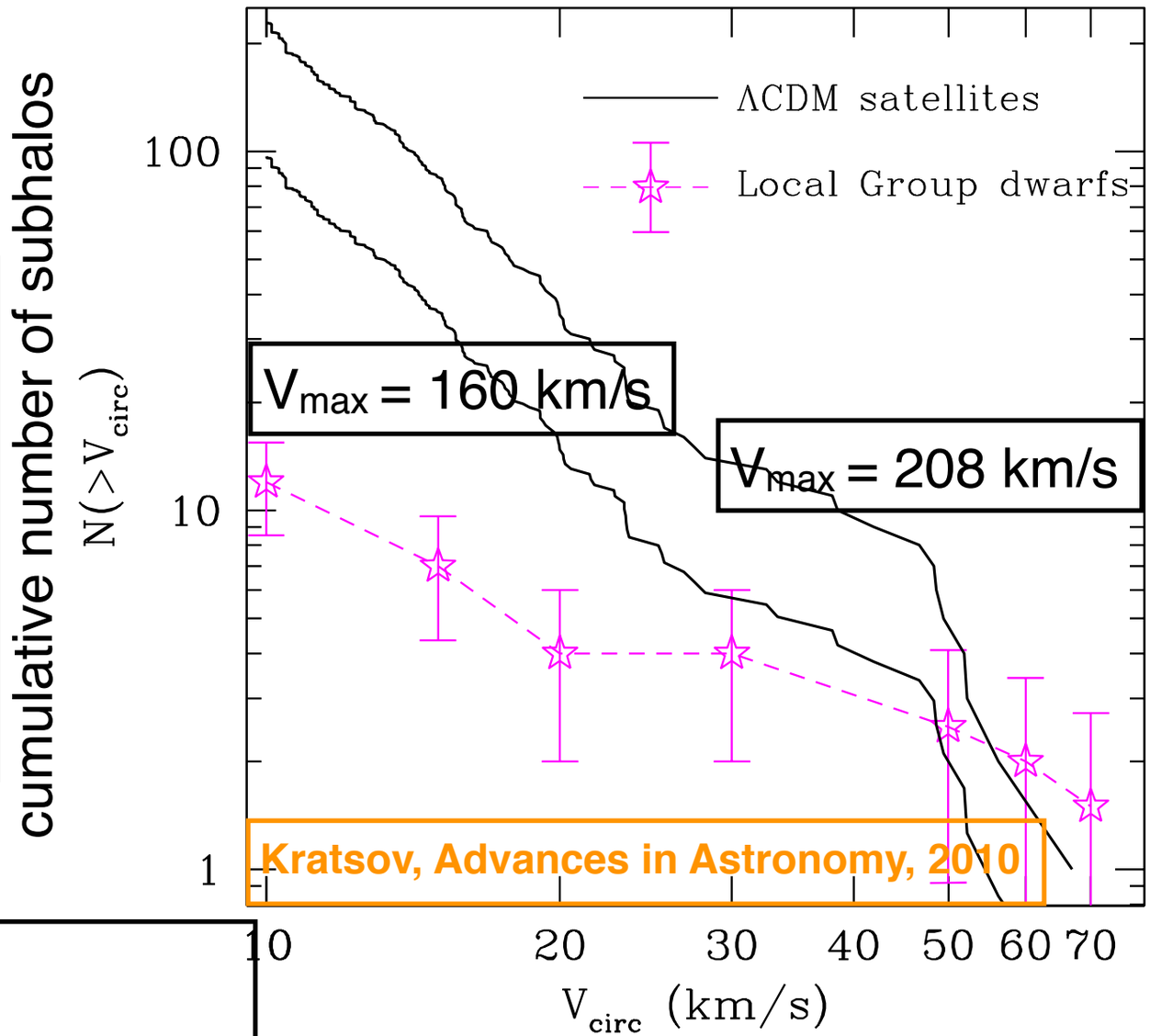


# Small scale crisis I

When *N*-body simulations in the ΛCDM model and observations are compared, problems appear at (sub-)galactic scales: **small scale crisis**

**missing satellite problem**

*N*-body (DM-only) simulations in the ΛCDM model →
Milky Way-size halos host O(10) times larger number of subhalos than that of observed dwarf spheroidal galaxies




(maximum) circular velocity

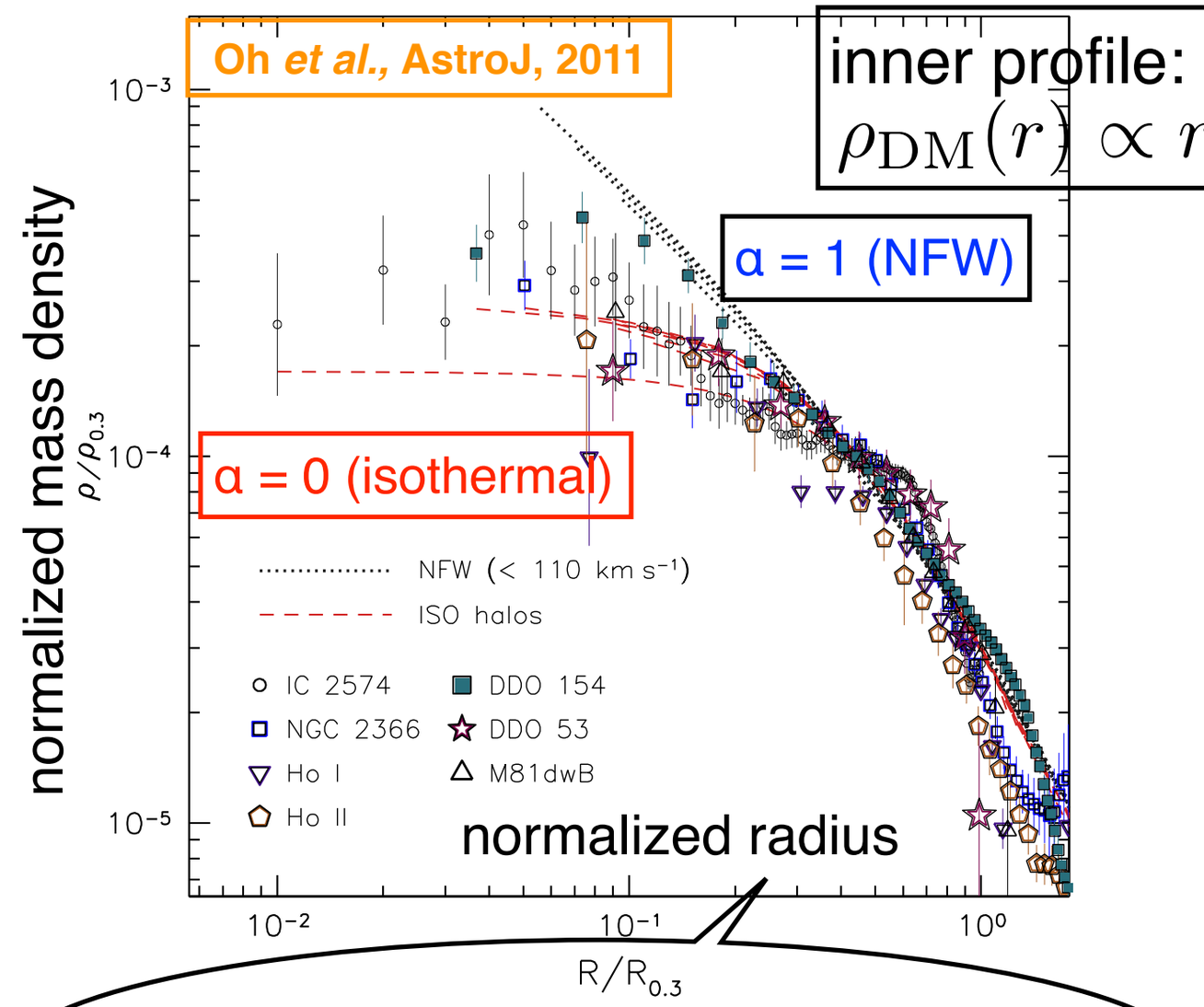
$$V_{\rm circ}^2(r) = \frac{GM(<r)}{r} \qquad V_{\rm max} = \max_r\{V_{\rm circ}(r)\}$$

maximal circular velocity of subhalo

# Small scale crisis II

## cusp vs core problem

N-body (DM-only) simulations in the ΛCDM model →
common DM profile independent of halo size: NFW profile




Observations infer cored profile in the inner region rather than cuspy NFW profile

NFW profile:

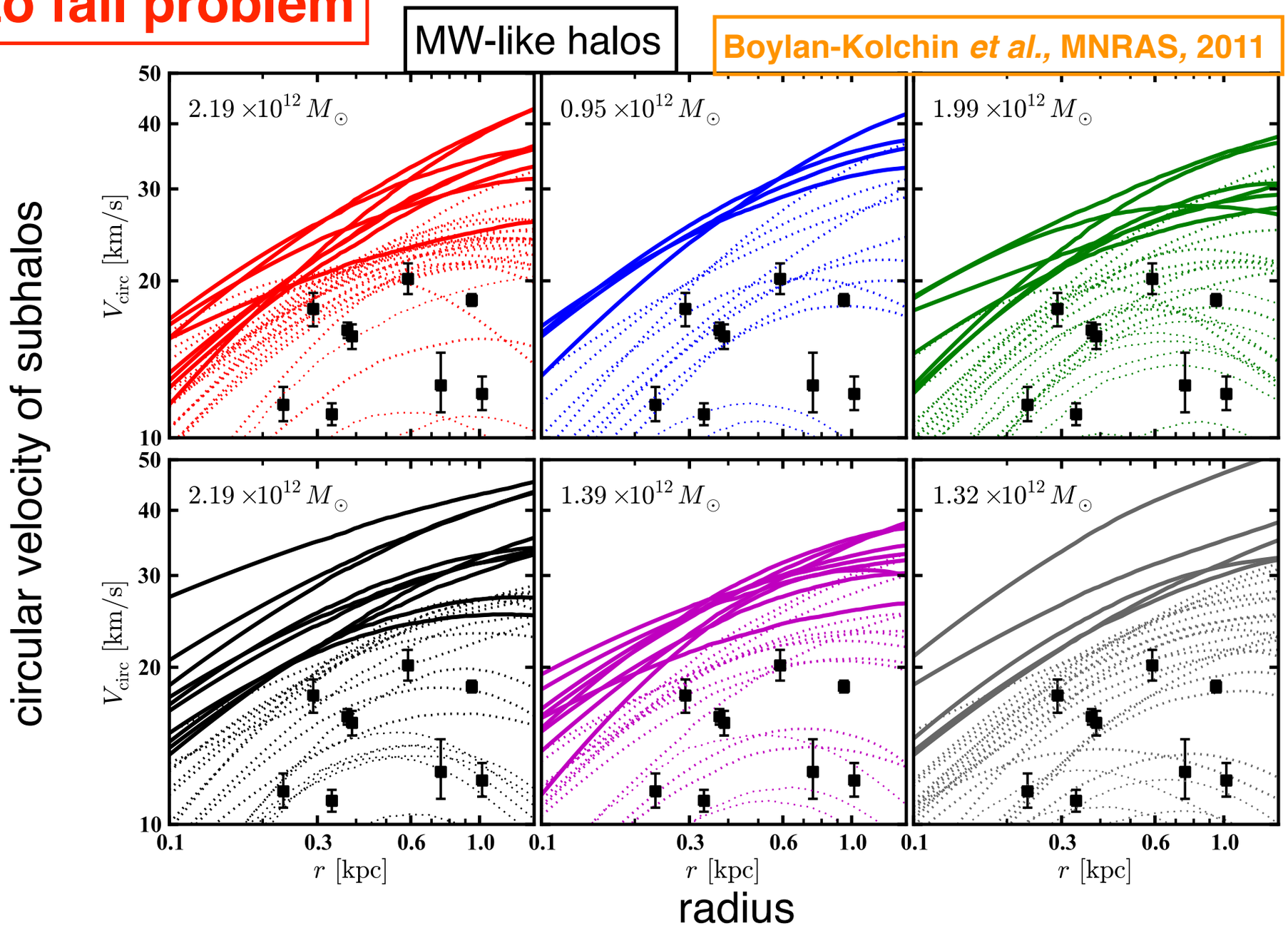
$$\rho_{\rm DM}(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

isothermal profile:

$$\rho_{\rm DM}(r) = \rho^0_{\rm DM} \begin{cases} 1 \ (r \ll r_0) \\ (r_0/r)^2 \ (r \gg r_0) \end{cases}$$

# Small scale crisis III

**too big to fail problem**




*N*-body (DM-only) simulations in ΛCDM model →
~10 subhalos with deepest potential wells in Milky Way-size halos
do not host observed counterparts (dwarf spheroidal galaxies)

# Concentration-mass relation

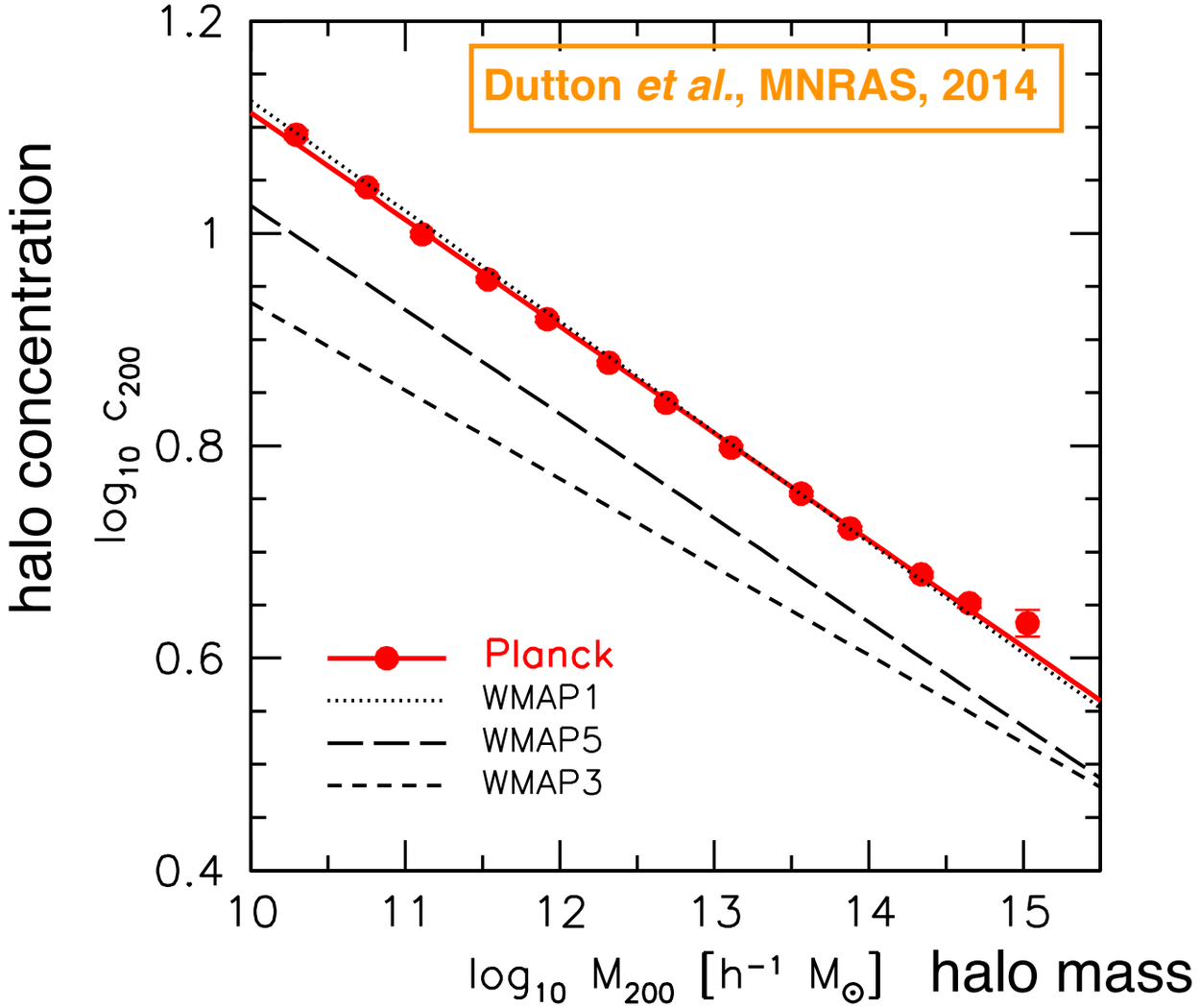
Why is a simulated rotation curve (almost) **DEFINITE** for a given $V_{max}$?
Two parameters for the NFW profile

$$\rho_{\rm DM}(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

A relation between two parameters usually given as
the **CONCENTRATION-MASS RELATION**

$$c_{200} = 10^{0.905\pm0.11}(M_{200}/10^{12}\,h^{-1}M_\odot)^{-0.101}$$

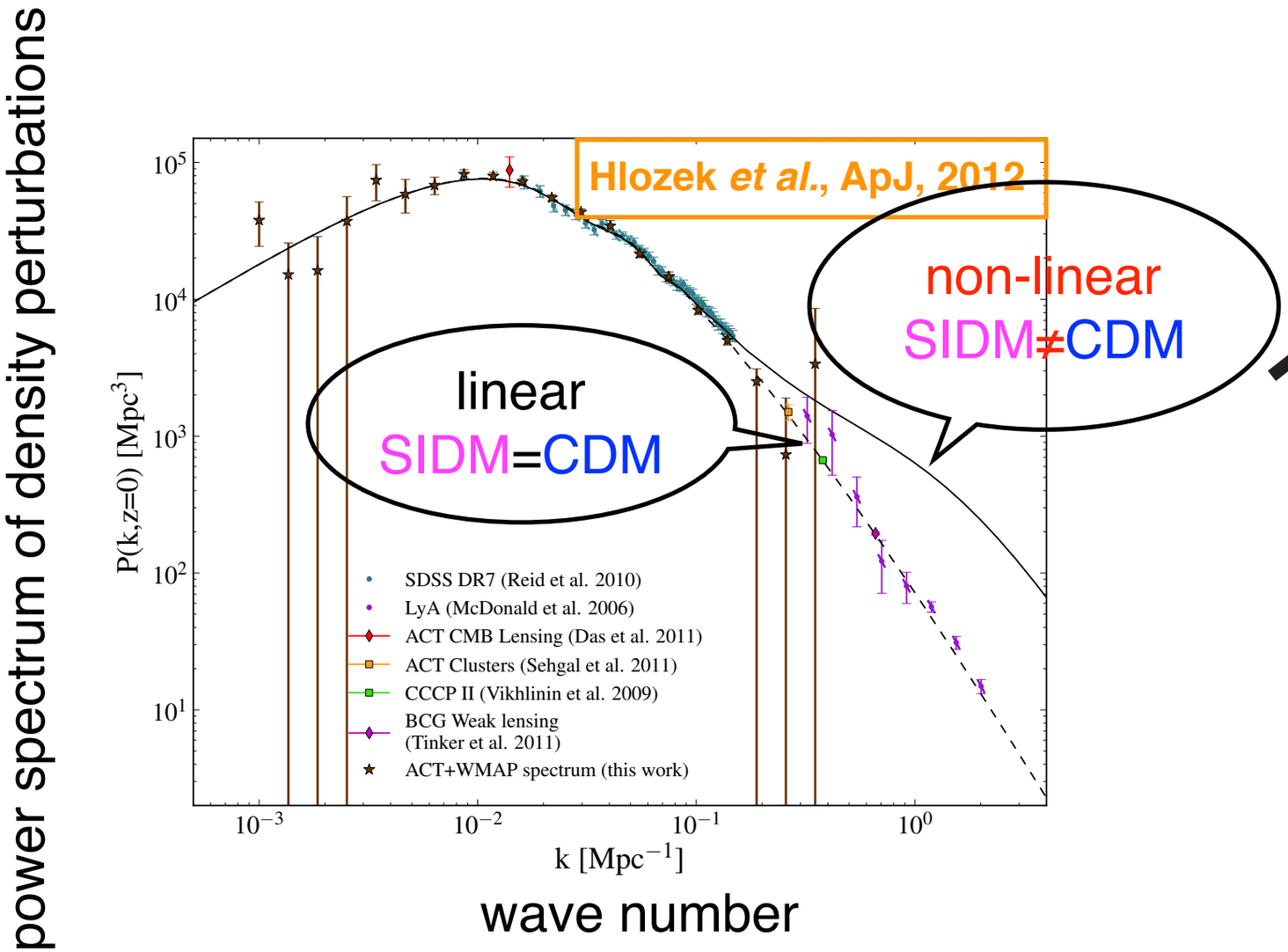
small
intrinsic scatter

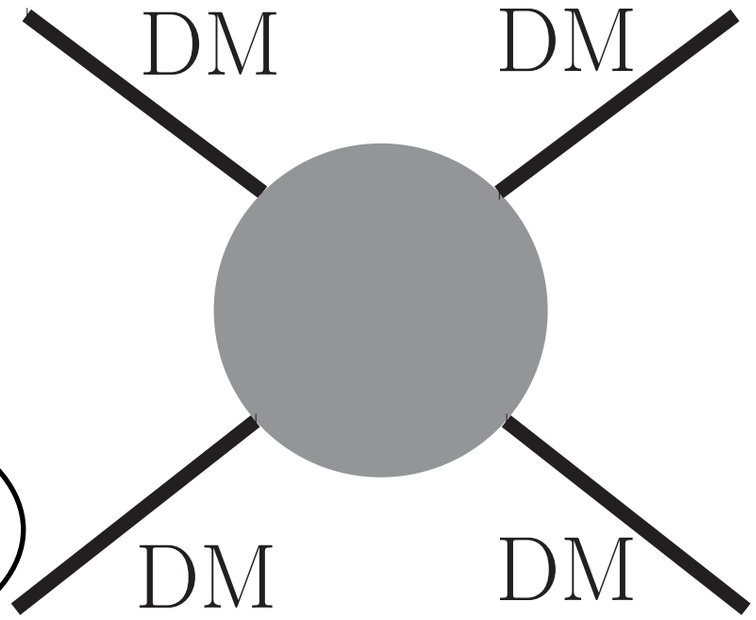



$$c_{200} = r_{200}/r_s$$
$$M_{200}(<r_{200}) = \frac{4\pi}{3}\bar{\rho}_{\rm M} r_{200}^3$$

# Dark matter self-interaction

Self-Interacting Dark Matter: SIDM




Reaction rate $\Gamma=\sigma v \rho/m$

σ: cross section

v: relative velocity

ρ: dark matter mass density

m: dark matter mass

SIDM structure formation starts with
the same linear (initial) matter power spectra as CDM,
but self-interactions become important
as structure formation proceeds ↔ ρ increases

# SIDM halo - velocity dispersion

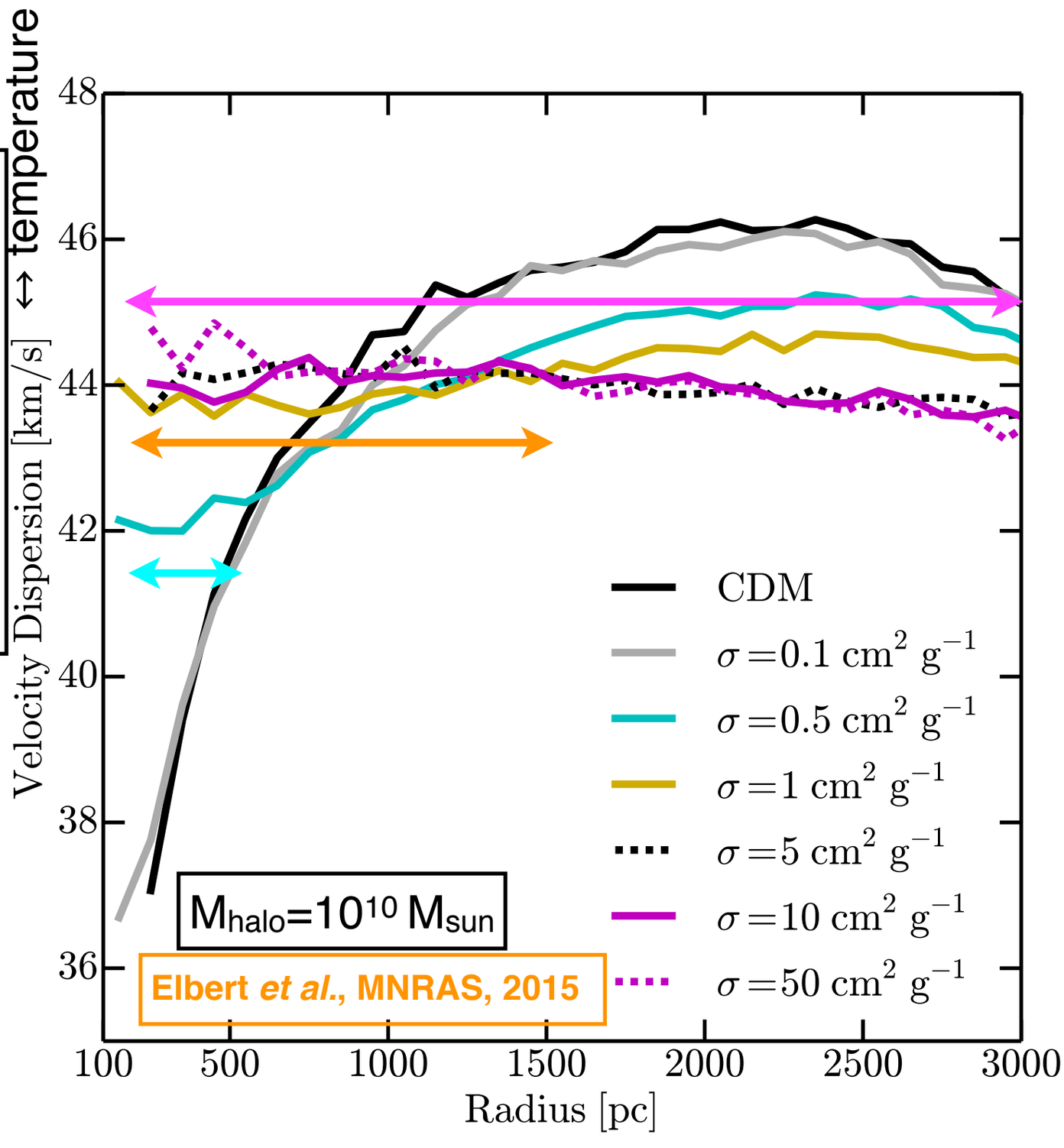
SIDM-only simulation

SIDM halos are **THERMALIZED** (isothermal) in inner region $r < r_1$, where the self-scattering is efficient $\sigma v \rho(r_1) t_{age}/m=1$

$t_{age}$=5 Gyr(galaxy cluster)
10 Gyr (galaxy)

If $r_1 > r_{max}$, the gravo-thermo instability is significant

$$V_{\rm circ}(r_{\rm max}) = V_{\rm max}$$

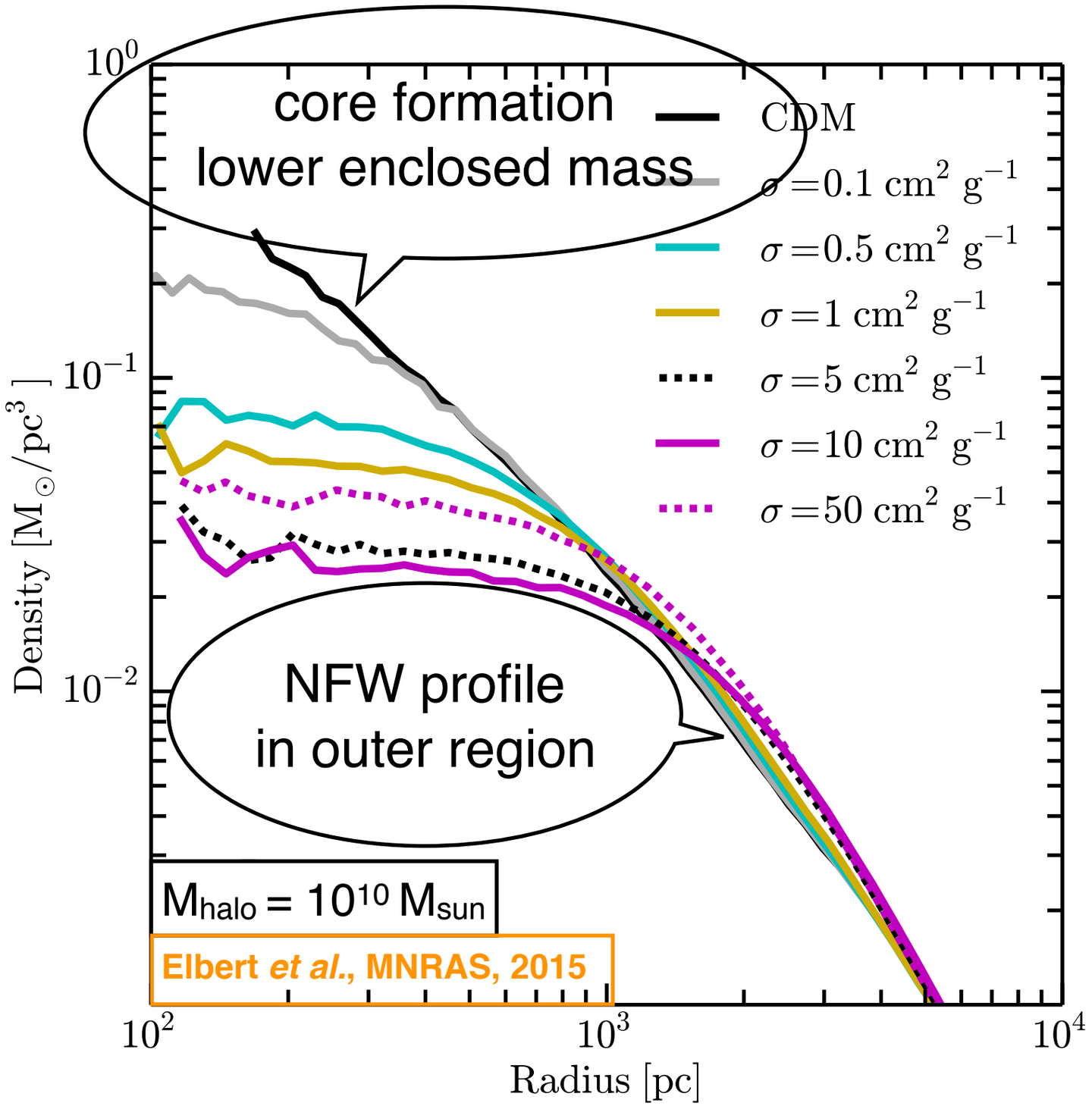


# SIDM halo - mass density

SIDM-only simulation

As σ/m increases,
central density decreases

Inverted at some point
← gravo-thermo instability
↔ core-collapse



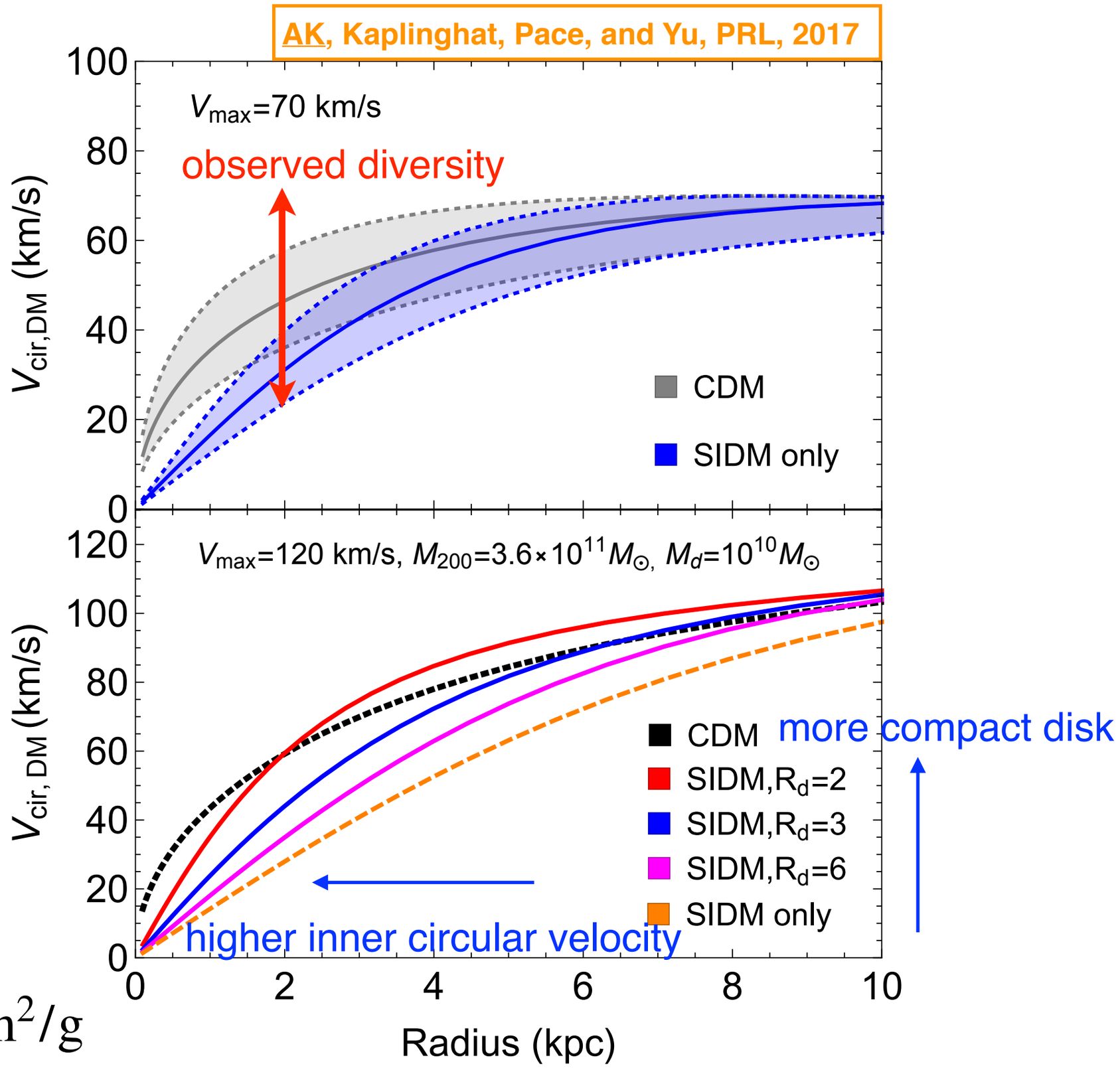

σ/m = 0.5-5 cm²/g may solve the inner mass deficit problem

# Demonstration with stellar disks

- observed diversity exceeds intrinsic diversity of DM halos

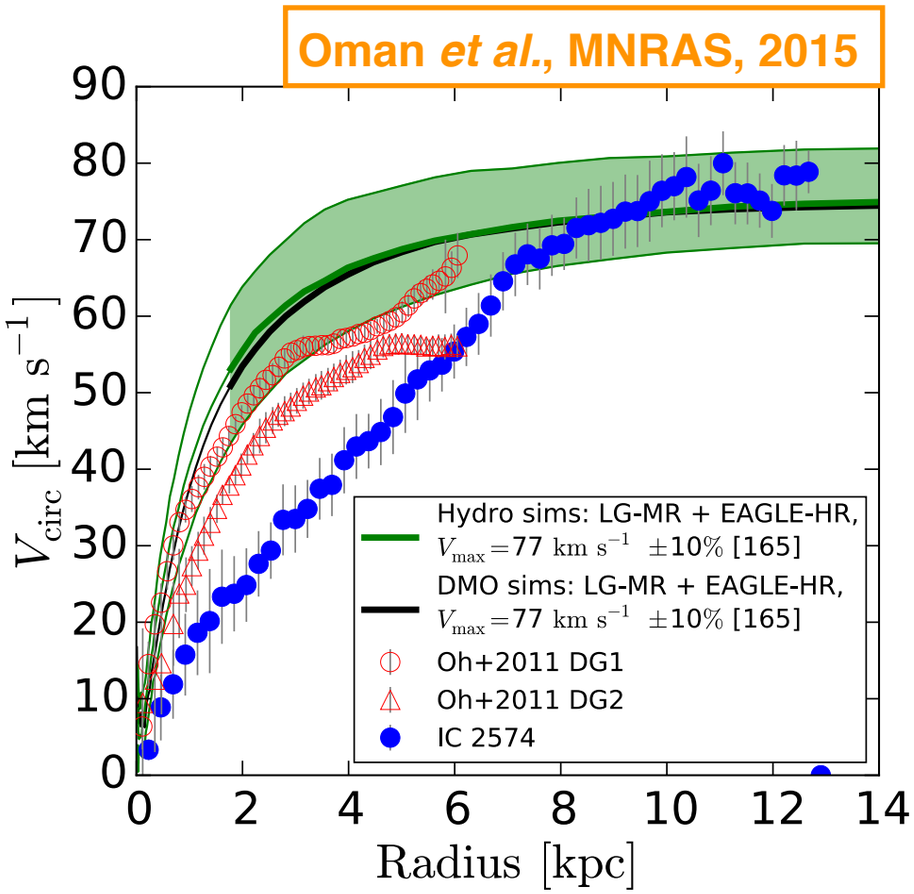
- compact disk can make SIDM inner circular velocity higher than the CDM prediction

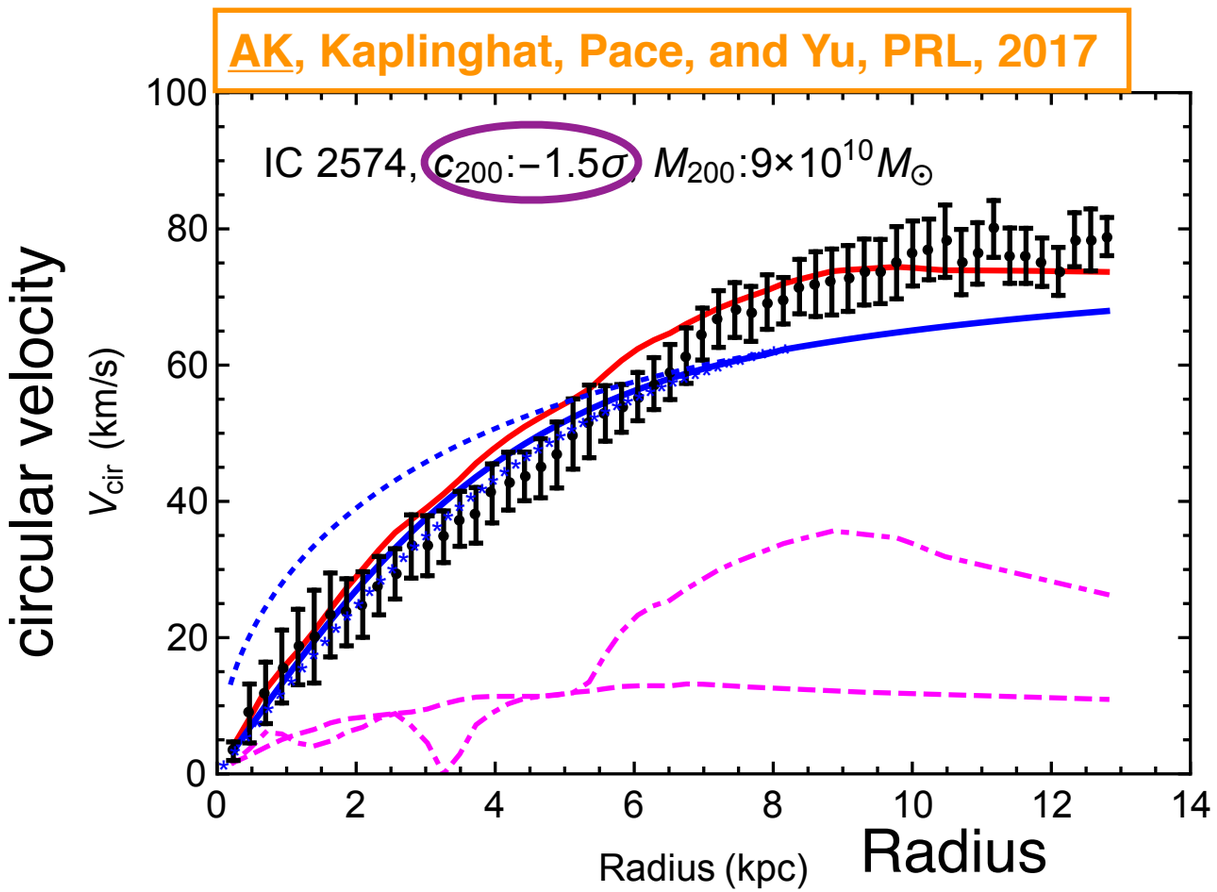
✳ Hereafter $\sigma/m = 3\,\mathrm{cm}^2/\mathrm{g}$

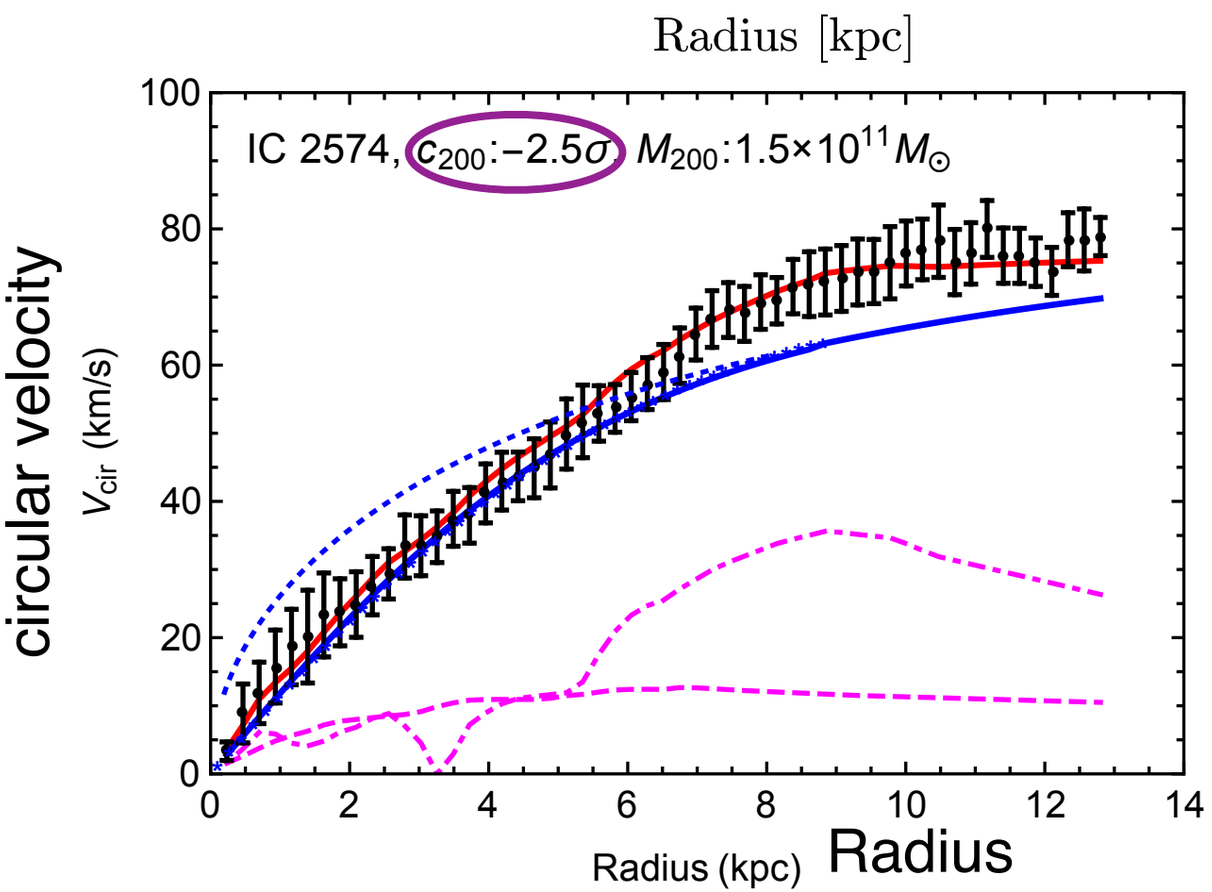


# Intrinsic scatter

Intrinsic diversity of DM halos should be taken into account to explain the observed diversity

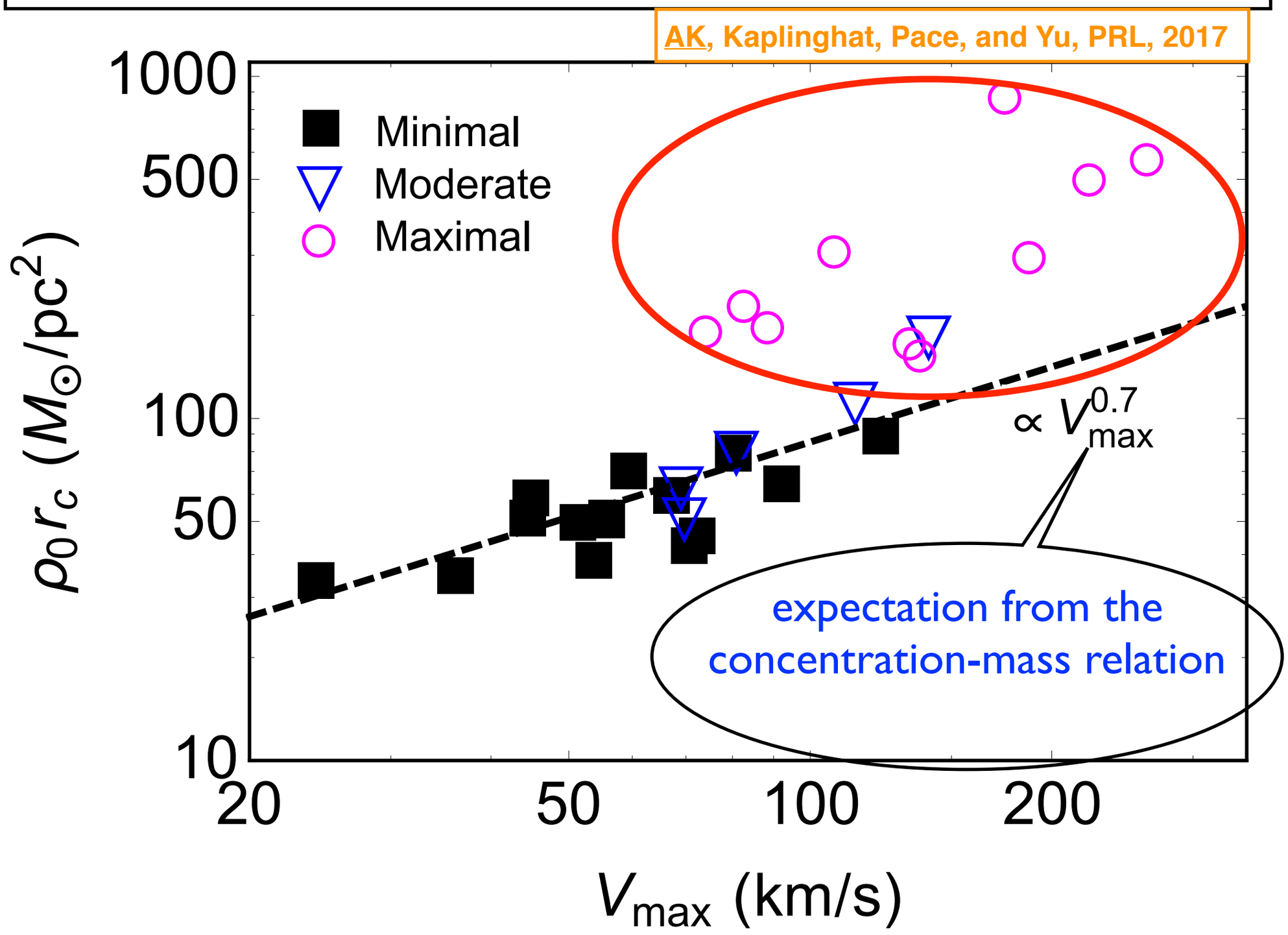


# More samples

Massive spiral galaxies, **GENERALLY**, make SIDM halos **VIOLATE** the concentration-mass relation



# Simple model

Model setup: QCD×QED-like hidden sector

- dark nucleons as DM

$$p' \sim u'u'd' \quad n' \sim u'd'd'$$

✳ discussion applies to isospin quartet DM

- small quark mass term

$$\mathscr{L}_{\text{mass}} = m_{u'} u'\bar{u}' + m_{d'} d'\bar{d}'$$

→ dark pions

$$\pi'^{+} \sim u'\bar{d}' \qquad \pi'^{0} \sim u'\bar{u}' - d'\bar{d}'$$

$$\pi'^{-} \sim d'\bar{u}'$$

| | $SU(3)_D$ | $U(1)_D$ | $U(1)_{B-L+B'}$ |
|---|---|---|---|
| $u'$ | **3** | 2/3 | 1/3 |
| $\bar{u}'$ | $\bar{\mathbf{3}}$ | −2/3 | −1/3 |
| $d'$ | **3** | −1/3 | 1/3 |
| $\bar{d}'$ | $\bar{\mathbf{3}}$ | 1/3 | −1/3 |

✳ naturalness → chiral theory

- SM copy

→ harmful neutrino's

# Generation and transfer of asymmetry

$$U(1)_{B-L+B'} \to (-1)^{3(B-L+B')}$$

Right-handed neutrinos $\overline{N}$ w/ soft breaking mass $M_R$

- thermal leptogenesis → $B-L$ asymmetry $T \sim M_R > 10^9\,\mathrm{GeV}$

  **Fukugita and Yanagida, PLB, 1986**

- see-saw mechanism → active neutrino mass $y_N LH\overline{N} \xrightarrow{\overline{N}} \dfrac{y_N^2}{M_R} LHLH$

- generation of the portal operator

$$y_N^2 \sim 10^{-5}\left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)\left(\frac{M_R}{10^9\,\mathrm{GeV}}\right)$$

Scalar down quark $H'_C$ w/ mass $M_{H'_C}$

$H'^{\dagger}_C \overline{u}'\overline{d}' \quad H'_C \overline{d}'\overline{N}$

$$\xrightarrow{H'_C} \frac{1}{M^2_{H'_C}} \overline{u}'\overline{d}'\overline{d}'\overline{N} \quad y_N LH\overline{N}$$

$$\xrightarrow{\overline{N}} \frac{y_N}{M^2_{H_C} M_R} \overline{u}'\overline{d}'\overline{d}' LH$$

| | $SU(3)_D$ | $U(1)_D$ | $U(1)_{B-L+B'}$ |
|---|---|---|---|
| $H'_C$ | **3** | $-1/3$ | $-2/3$ |

$U(1)_{B-L+B'}$

✗ $H'_C u'd' \quad H'^{\dagger}_C d'\overline{N}$

$$\to \frac{1}{M_*^3} u'd'd'LH$$

✳ decoupling after leptogenesis $M_{H_C} \sim M_R$

# Entropy transfer

$U(1)'$ breaking scalar $H^{+'}$ $\qquad \mathscr{L}_{A'} = \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{m_{\gamma'}}{2} A'_{\mu} A'^{\mu}$

Dark pions annihilate/decay into dark photon $m_{\gamma'} < m_{\pi'}$

$$\rightarrow \quad \Gamma_{\gamma' \to e\bar{e}} = 0.3\,\mathrm{s}^{-1} \times \left(\frac{\epsilon}{10^{-10}}\right)^2 \left(\frac{m_{\gamma'}}{100\,\mathrm{MeV}}\right)$$

- decay after neutrino decoupling $T \sim 1\,\mathrm{MeV} \leftrightarrow t \sim 1\mathrm{s}$

→ transferred entropy heating only $e$ and $\gamma$

→ lower bound on $\Gamma_{\gamma' \to e\bar{e}}$

- decay before neutrino decoupling

→ thermalized dark photon heating only $e$ and $\gamma$

→ lower bound on $m_{\gamma'}$

# DM direct detection

$p' \underset{\epsilon}{\times} p$ interaction

- DM direct detection → upper bound on $\epsilon$

- DM mass: $\frac{1}{M_{H'_C}^2 M_R} \bar{u}'\bar{d}'\bar{d}'LH \rightarrow \; m_{\rm DM} \simeq 8.5\,{\rm GeV}$ **Weinberg, "Cosmology"**

- $Y_{p'}/Y_{n'}$: freezes out at decoupling of conversion processes

$Y_{p'}/Y_{n'} = e^{(m_{n'}-m_{p'})/T}$ $\quad T \sim m_{\pi'}/20\text{-}30 \leftrightarrow$ dark pion decoupling

$m_{n'} - m_{p'} = \mathcal{O}(m_{u'/d'})$ $\quad m_{\pi'}^2 = \mathcal{O}\left(m_{u'/d'}\Lambda_{\rm QCD'}\right)$ → $Y_{p'}/Y_{n'} \sim 1$ for reference

c.f. $m_n - m_p \simeq 1.2\,{\rm MeV}$ $\quad m_\pi \simeq 140\,{\rm MeV}$

✳ if $m_{\gamma'} < B_{d'}$ , dark nucleosynthesis proceeds

**Krnjaic and Sigurdson, PLB, 2015…**

- impacting DM direct detection

# Charge of breaking scalar

Ibe, AK, Kobayashi, Kuwahara and Nakano, work in progress

$U(1)_D$ charge determines $\pi'$-$\widetilde{e}$ mixing

$SU(4)$

| | $SU(3)_D$ | $U(1)_D$ | $U(1)_{B-L+B'}$ |
|---|---|---|---|
| $\widetilde{e}$ | $\mathbf{1}$ | $-1$ | $0$ |

→ Yukawa interactions $\widetilde{e}' u' \bar{d}'$ $\widetilde{e}'^{\dagger} \bar{u}' d'$

- entropy transfer through $\pi'$-$\widetilde{e}$ mixing
  + Higgs portal $|\widetilde{e}'|^2 |H|^2$

- DM direct detection through Higgs portal?

# SUSY mass spectrum

Arkani-Hamed and Dimopoulos, JHEP, 2005 | Giudice and Romanino, NPB, 2004 | Wells, PRD, 2005 | ...

Mini-split SUSY mass spectrum:

sfermions, heavy Higgses > 100 TeV; gravitino > 100 TeV

- 125 GeV Higgs although naturalness unanswered

gauginos ~ TeV; higgsino ~TeV

- precise $SU(5)$ grand unification

- LSP and LSP' abundance: small enough

- LSP → LSP' or vice versa long before big bang nucleosynthesis

$$\tau \sim 2 \times 10^{-3}\,\mathrm{s} \left( \frac{10^{-10}}{\epsilon} \right)^2 \left( \frac{10^3\,\mathrm{GeV}}{M_{\mathrm{light}\,S}} \right)^2$$